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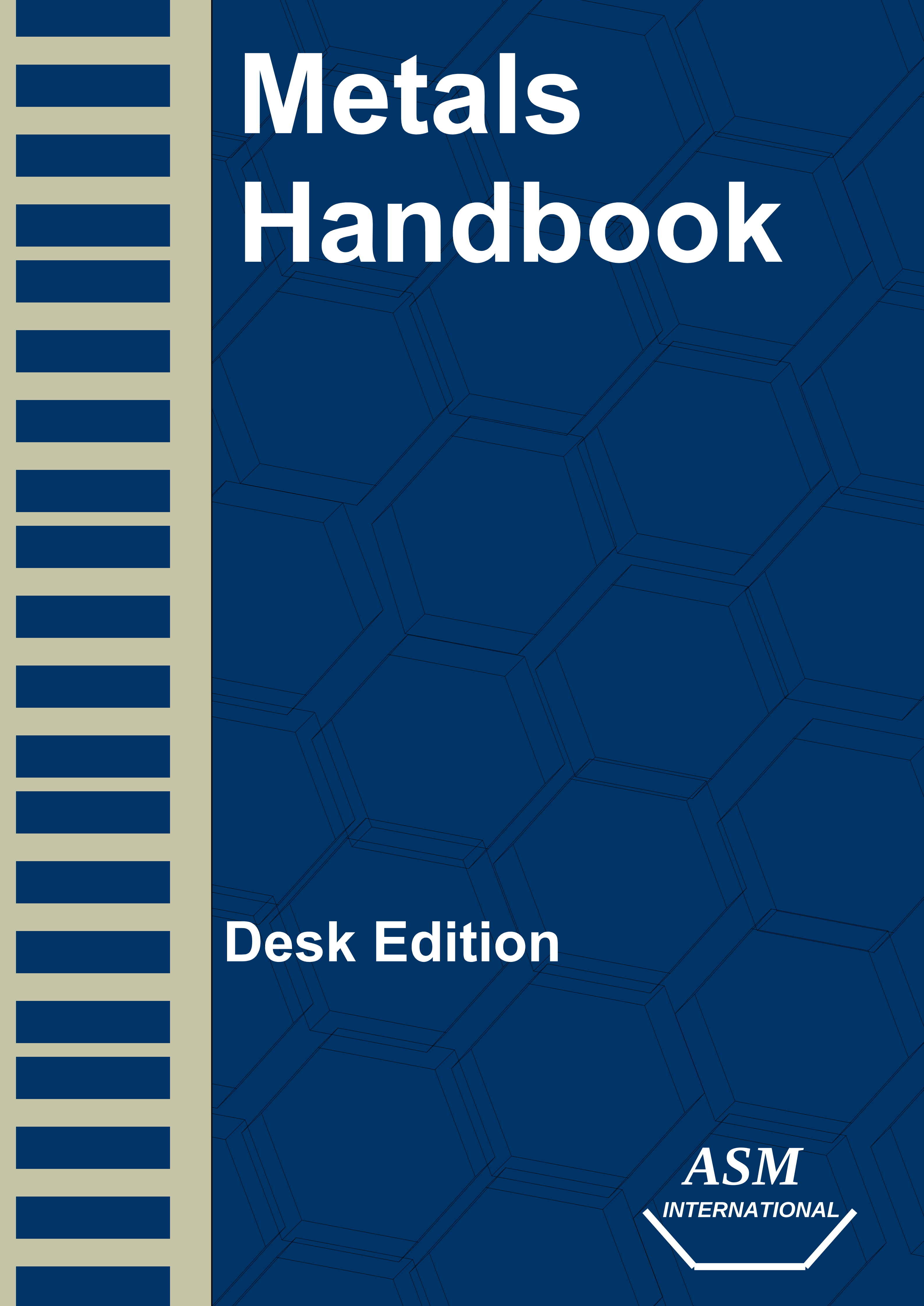

Metals Handbook

Desk Edition

ASM INTERNATIONAL

Metals Handbook Desk Edition, Second Edition was published in 1998. It was prepared under the direction of the ASM International Handbook Committee. The *Desk Edition* was edited by Joseph R. Davis.

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Foreword to the Print Edition

ASM International is proud to mark the 75th anniversary of ASM Handbooks. In 1923, the American Society for Steel Treating (later the American Society for Metals, now ASM International) published a small loose-leaf collection of data sheets--the first edition of what became known as *Metals Handbook.* The series has developed over the years into a multivolume collection of reference books--each volume a thorough, comprehensive, and authoritative treatise on the subject to which it is devoted. The series--now titled *ASM Handbook*--continues to evolve and expand to serve the changing needs of metallurgy professionals throughout the world. One example of this evolution is the release this year of the *ASM Handbook* on CD-ROM.

This year also marks the 50th anniversary of the classic 1948 edition of *Metals Handbook*--the last "regular" edition to be contained in one volume. The 1948 edition was the inspiration for the first *Metals Handbook Desk Edition,* published almost 15 years ago. This Second Edition is intended to serve the same function as its two predecessors: to provide an accessible, convenient, and practical single-volume first reference to all of metals technology.

It was with some trepidation that ASM International entered into the project to revise and update the *Desk Edition.* The task seemed overwhelming. The *ASM Handbook* series had grown to 20 current volumes--almost twice as many as were in existence when the first *Desk Edition* was compiled. Would it be possible to create a work that included all of the vital information from the first edition, plus the most significant knowledge and data compiled in the years since its release, and still remain within the physical limits of a single volume?

We believe that the new *Metals Handbook Desk Edition*more than meets that objective. The credit for this monumental achievement belongs to Joseph R. Davis. Joe was Handbook Editor for many years at ASM, and his extraordinary knowledge of the handbooks along with his considerable editorial skills made him uniquely qualified to oversee this project. We are grateful to Joe for his hard work and for his commitment to creating the best *Desk Edition* possible. To assist in this effort, Joe assembled an outstanding Editorial Advisory Board, made up of many longtime handbook contributors and friends of ASM, and we extend our thanks to them as well. We also wish to recognize the ASM editorial and production staff members for their dedicated efforts on this Volume.

Of course, we are especially grateful to the thousands of metallurgy professionals who have contributed to ASM Handbooks over the past 75 years. Their willingness to share their knowledge and expertise--as authors, reviewers, volume organizers, and Handbook Committee members--has made this book possible. With their ongoing support, ASM Handbooks will continue to thrive for at least another 75 years.

Alton D. Romig, Jr.
President, ASM International

Michael J. DeHaemer
Managing Director, ASM International

Preface

The *Metals Handbook Desk Edition* is intended to serve as a comprehensive single-volume reference source on the properties, selection, processing, testing, and characterization of metals and their alloys. Although the information presented in this Volume is drawn principally from the 20 volumes of the *ASM Handbook* series, it should not be considered simply an abridged version of the larger work. Instead, the *Metals Handbook Desk Edition* draws upon the complete arsenal of ASM products--both print and electronic--as well as other key sources of information originating from other publications, company literature, technical societies, and government agencies.

Volume Content

Because of the familiarity, success, and ease-of-use of the original *Desk Edition* published in 1984, it was determined from the outset of the project that the editorial approach and outline for the new edition should follow in a similar manner. The challenge in successfully revising the first edition was to determine what strategic additions (or reductions)and improvements should be made. Complicating this task was the fact that a complete edition cycle of the *ASM Handbook* (including completely new volumes on corrosion, tribology, materials characterization, and other topics) had been published since the earlier edition was produced. To ensure that the best product possible resulted from the revision/updating process, a 12-member Editorial Advisory Board representing industry, academia, and research laboratories was formed. All board members have been key contributors to the Handbook series or have been involved with other important ASM activities over the past decade. Under their guidance, an outline was established for the second edition that divided the book into five major parts: General Information; Irons, Steels, and High-Performance Alloys; Nonferrous Alloys and Special-Purpose Materials; Processing; and Testing, Inspection, and Materials Characterization.

General Information contains a glossary of more than 3000 terms, a collection of common engineering tables, and graphs comparing properties of metals and nonmetals. It also includes contributions on crystal structure, practical uses of phase diagrams, engineering design, and factors to be considered in the materials selection process.

Irons, Steels, and High-Performance Alloys. Emphasis is placed on properties and selection of ferrous alloys and heat-resistant superalloys. Important relationships between structure and properties in irons and steels are described. The effects of modern steelmaking practices on properties are examined, as is the influence of improved melting/refining methods on superalloy performance. New or expanded information is presented on austempered ductile irons, high-strength low-alloy steels, stainless steels(including duplex stainless steels), and powder metallurgy steels.

Nonferrous Alloys and Special-Purpose Materials comprises 14 major sections that describe the properties and selection of conventional (structural) nonferrous alloys and materials used for such special-purpose applications as magnetic or electrical devices, biomedical devices, and advanced aircraft/aerospace components. Metal-matrix composites and structural intermetallics--more recently developed materials not covered in the previous *Desk Edition*--are also described.

Processing. Processes extending through the entire life-cycle of a component are described, including extractive metallurgy, casting, forming, heat treatment, joining, surface cleaning, finishing and coating, and recycling. An entirely new section on powder metallurgy has also been added. The increased coverage of recycling technology reflects the response of the metals industry to environmental concerns.

Testing, Inspection, and Materials Characterization. In addition to offering information on failure analysis, fractography, nondestructive testing, mechanical testing, and metallography, a new section describes in practical terms the selection of characterization methods for bulk elemental analysis, bulk microstructural analysis, and surface analysis. New information on wear testing and tests for evaluating stress-corrosion cracking and hydrogen embrittlement is also presented.

Acknowledgments

Before acknowledging contributors to the present volume, it is important to recognize the outstanding work of the first edition's editors: Timothy L. Gall and Howard E. Boyer (sadly, Howard passed away in 1990). Tim was truly the driving force behind the original *Desk Edition.* His vision, combined with Howard's superlative technical craftsmanship, resulted in what most consider the "flagship" publication of ASM.

In order to build upon the foundation of the first edition, the present editor had to call on many old friends and colleagues. In addition to serving on the Editorial Advisory Board, the following individuals were major contributors to the second edition: Kenneth H. Eckelmeyer (Sandia National Laboratories)authored the Section "Materials Characterization" and co-authored the article "Very High Density Metals." Ken, who has contributed numerous handbook articles over the years, was also a key member of the Organizing Committee for *Materials Characterization,* Volume 10 of the *ASM Handbook,* published in 1986. George F. Vander Voort (Buehler Ltd.) revised the Section "Metallography" and contributed to the Section "Fractography." George, who is the most prolific author in the 75 year history of the *Metals/ASM Handbook,* has contributed definitive reviews on embrittlement mechanisms in irons and steel, the use of light microscopy for metallographic and fractographic analysis, and image analysis for quantitative determination of microstructural constituents. Rodney R. Boyer (Boeing Commercial Airplane Group) revised the Section "Titanium and Titanium Alloys" and helped revise other articles throughout the Handbook that deal with titanium alloys. Rod also served as the principal editor of the *Materials Properties Handbook: Titanium Alloys,*published by ASM in 1994. Thomas S. Piwonka (University of Alabama) authored the Section "Casting." Tom also served as a section chairman and contributing author for *Casting,* Volume 15 of the *ASM Handbook,* published in 1988. Peter J. Blau (Oak Ridge National Laboratory) authored the article "Wear Testing." Peter also served as volume chairman of *Friction, Lubrication, and Wear Technology,* Volume 18 of the *ASM Handbook,* published in 1992.

Other notable contributors include Hugh Baker (Consulting Editor, ASM International), who authored the Section "Structure and Properties of Metals" and reviewed the Section "Magnesium and Magnesium Alloys."Hugh, who served on the Handbook staff from 1970 to 1979, was also the editor of *Alloy Phase Diagrams,* Volume 3 of *ASM Handbook,* published in 1992. Matthew J. Donachie (Rensselaer at Hartford)and Stephen J. Donachie (Special Metals Corporation) revised the Section "Superalloys."Matt, who edited the *Superalloys Source Book* published by ASM in 1984, also authored the article "Biomaterials." Erhard Klar (OMG Americas, retired) authored the Section "Powder Metallurgy"and reviewed several other P/M-related articles. Erhard also served as volume coordinator of *Powder Metallurgy,* Volume 7 of the *ASM Handbook,* published in 1984. Brajendra Mishra (Colorado School of Mines) authored the Sections "Steelmaking Practices and Their Influence on Properties" and "Extractive Metallurgy." John C. Bittence(Welshfield Studios) revised the Section "Recycling and Life-Cycle Analysis"and assisted in editing the Sections "Forming" and "Forging."

The efforts of the ASM staff must also be acknowledged. In particular, I would like to thank veteran technical editors Steven R. Lampman and Edward J. Kubel, Jr. for their help in completing the Sections "Failure Analysis,""Nondestructive Testing," and "Mechanical, Wear, and Corrosion Testing," and Scott D. Henry, Assistant Director of Technical Publications, for his unflagging support and patience throughout the project. The kind assistance of the ASM Library is also duly noted.

As a result of the collective experience and talent of all those listed above, the rich tradition of the *Metals Handbook* continues. Whether in print form, CD-ROM format, via the Internet, or some other remarkable vehicle made possible by the computer age, it will undoubtedly continue to serve the metallurgical community well into the next millennium. The best is yet to come!

Joseph R. Davis
Davis & Associates, Chagrin Falls, Ohio

Source Acknowledgments

Major sources for the Sections in this Handbook are listed below. Additional source information is provided in the reference lists that appear in many of the articles.

Structure and Properties of Metals

Much of this Section was adapted from *Alloy Phase Diagrams,* Volume 3, *ASM Handbook,* 1992, pages 1-1 to 1-29.

Design Considerations and Materials Selection

Much of this Section was adapted from various articles appearing in *Materials Selection and Design,* Volume 20, *ASM Handbook,* 1997.

Structure/Property Relationships in Irons and Steels

Much of this Section was adapted from various articles appearing in *Materials Selection and Design,* Volume 20, *ASM Handbook,* 1997, pages 357-382.

Carbon and Alloy Steels

This Section was condensed from *Properties and Selection: Irons, Steels, and High-Performance Alloys,* Vol 1, *ASM Handbook,* 1990, pages 105 to 822. Supplemental information was also adapted from the *ASM Specialty Handbook: Carbon and Alloy Steels,*1996, and *Fatigue and Fracture,* Vol 20, *ASM Handbook,* 1996.

Cast Irons

This Section was condensed from the *ASM Specialty Handbook:Cast Irons,* 1996, p 3 to 130.

Ferrous Powder Metallurgy Materials

This Section was condensed from *Properties and Selection: Irons, Steels, and High-Performance Alloys,* Volume 1, *ASM Handbook,* 1990, pages 800 to 821 and from *Powder Metallurgy,*Volume 7, *ASM Handbook,* 1984, pages 79 to 99.

Tool Steels

This Section was condensed from the *ASM Specialty Handbook:Tool Materials,* 1995, pages 10 to 20, 21 to 31, 119 to 153, and 383 to 395.

Stainless Steels

Much of this Section was condensed from the *ASM Specialty Handbook:Stainless Steels,* 1994. Supplemental information was also adapted from the *ASM Specialty Handbook: Heat-Resistant Materials,*1997, pages 123 to 178.

Superalloys

For more detailed information on superalloys, the reader is referred to the *ASM Specialty Handbook: Heat-Resistant Materials* (see, in particular, pages 219 to 344).

Aluminum and Aluminum Alloys

This Section was assembled from a variety of sources, including *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 3 to 215; the *ASM Specialty Handbook: Aluminum and Aluminum Alloys,* 1993, pages 3 to 159; and *Corrosion,* Volume 13, *ASM Handbook,* 1987, pages 583 to 609. Updated statistical information and property data were obtained from the Aluminum Association Inc.

Copper and Copper Alloys

This Section was assembled from a variety of sources, including *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 216 to 427, *Corrosion,* Volume 13, *ASM Handbook,* 1987, pages 610 to 640, and *Materials Selection and Design,* Volume 20, *ASM Handbook,* 1997, pages 389 to 393. Updated statistical information and composition/property data were obtained from the Copper Development Association Inc.

Magnesium and Magnesium Alloys

This Section was condensed from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 455 to 479, and from *Corrosion,* Volume 13, *ASM Handbook,* 1987, pages 740 to 754.

Titanium and Titanium Alloys

For more detailed information on titanium and titanium alloys, the reader is referred to the *Materials Properties Handbook: Titanium Alloys* published by ASM International in 1994 and to *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2 of *ASM Handbook,* 1990 (see pages 586 to 660).

Zinc and Zinc Alloys

This Section was condensed from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 527 to 542, and from *Corrosion,* Volume 13, *ASM Handbook,* 1987, pages 432 to 445 and 755 to 769.

Tin and Tin Alloys

This Section was condensed from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 517 to 526.

Lead and Lead Alloys

This Section was condensed from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 543 to 556, and from *Corrosion,* Volume 13, *ASM Handbook,* 1987, pages 784 to 792.

Nickel and Nickel Alloys

This Section was condensed from *Corrosion,* Volume 13, *ASM Handbook,* 1987, pages 641 to 657, and *Materials Selection and Design,* Volume 20, *ASM Handbook,* 1997, pages 393 to 396.

Cobalt and Cobalt Alloys

This Section was condensed from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 446 to 454.

Zirconium and Hafnium

This Section was condensed from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 661 to 669, and from *Corrosion,* Volume 13, *ASM Handbook,* 1987, p 707 to 721.

Precious Metals and Alloys

This Section was condensed from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 688 to 719.

Refractory Metals and Alloys

This Section was condensed from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 557 to 585, and from the *ASM Specialty Handbook:Heat-Resistant Materials,* 1997, pages 361 to 382.

Cemented Carbides and Cermets

This Section was condensed from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 950 to 977, and from *Friction, Lubrication, and Wear Technology,* Volume 18, *ASM Handbook,* 1992, pages 795 to 800.

Special-Purpose Materials

Portions of this Section were condensed from *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 761 to 1089. Supplemental information was also adapted from the *ASM Specialty Handbook: Aluminum and Aluminum Alloys,* 1993, pages 160 to 179 (aluminum-matrix composites), *ASM Specialty Handbook: Heat-Resistant Materials,* 1997, p 389 to 414 (structural intermetallics), and *Friction, Lubrication, and Wear Technology,* Volume 18, *ASM Handbook,* 1992, pages 741 to 765 (sliding bearings and hardfacing alloys).

Forming

This Section was condensed from *Forming and Forging,*Volume 14, *ASM Handbook,* 1988.

Forging

This Section was condensed from *Forming and Forging,*Volume 14, *ASM Handbook,* 1988.

Powder Metallurgy

More detailed information on powder metallurgy can be found in *Powder Metal Technologies and Applications,* Volume 7, *ASM Handbook,* 1998.

Machining

This Section was condensed from *Machining,* Volume 16, *ASM Handbook,* 1989, and the *Machining Data Handbook,*3rd ed., published by Metcut Research Associates, Inc., Cincinnati, OH. Supplemental information was also taken from *Surface Engineering,* Volume 5, *ASM Handbook,* 1994, and the *ASM Specialty Handbook:Tool Materials,* 1995.

Heat Treating

This Section was condensed from *Heat Treating,* Volume 4, *ASM Handbook,* 1991.

Joining

This Section was condensed from *Welding, Brazing, and Soldering,* Volume 6, *ASM Handbook,* 1993.

Surface Engineering

This Section was condensed from *Surface Engineering,*Volume 5, *ASM Handbook,* 1994. Supplemental information was also taken from *Materials Selection and Design,* Volume 20, *ASM Handbook,* 1997, pages 470 to 490.

Recycling and Life-Cycle Analysis

This Section was condensed from *Properties and Selection: Irons, Steels, and High-Performance Alloys,* Volume 1, *ASM Handbook,* 1990, pages 1023 to 1033; from *Properties and Selection:Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* 1990, pages 1205 to 1232; and from *Materials Selection and Design,* Volume 20, *ASM Handbook,* 1997, pages 96 to 103 and 131 to 138.

Failure Analysis

This Section was condensed from *Failure Analysis and Prevention,* Volume 11, *ASM Handbook,* 1986, and *Fatigue and Fracture,* Volume 19, *ASM Handbook,* 1996, pages 371 to 380.

Fractography

Parts of this Section were condensed from *Fractography,*Volume 12, *ASM Handbook,* 1987. Updated material from the previous *Metals Handbook Desk Edition,* 1984, is also included.

Nondestructive Testing

This Section was condensed from *Nondestructive Evaluation and Quality Control,* Volume 17, *ASM Handbook,* 1989.

Mechanical, Wear, and Corrosion Testing

This Section was condensed from *Mechanical Testing,*Volume 8, *ASM Handbook,* 1985, and from *Fatigue and Fracture,* Volume 19, *ASM Handbook,* 1996.

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Conversion to Electronic Files

Metals Handbook Desk Edition was converted to electronic files in 2000. The conversion was based on the first printing (1998). No substantive changes were made to the content of the Volume, but some minor corrections and clarifications were made as needed.

ASM International staff who contributed to the conversion of the Volume included Sally Fahrenholz-Mann, Bonnie Sanders, Marlene Seuffert, Gayle Kalman, Scott Henry, and Robert Braddock. The electronic version was prepared under the direction of William W. Scott, Jr., Technical Director, and Michael J. DeHaemer, Managing Director.

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First printing, December 1998

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Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

Library of Congress Cataloging-in-Publication Data (for Print Volume)

Metals handbook/edited by J.R. Davis; prepared under the direction of the ASM International Handbook Committee.--Desk ed.; 2nd ed. Includes bibliographical references and index.

1. Metals--Handbooks, manuals, etc. I. Davis, J.R.

II. ASM International. Handbook Committee.

TA459.M288 1998 620.1'6 dc21 98-45866

SAN 204-7586

ISBN 0-87170-654-7

Engineering Data for Metals and Alloys

Table 1 Density of metals and alloys

Metal or alloy	Density	
	g/cm^3	lb/in.^{3}
Aluminum and aluminum alloys		
Aluminum (99.996%)	2.6989	0.0975
Wrought alloys		
EC, 1060 alloys	2.70	0.098
1100	2.71	0.098
2011	2.82	0.102
2014	2.80	0.101
2024	2.77	0.100
2218	2.81	0.101
3003	2.73	0.099
4032	2.69	0.097
5005	2.70	0.098
5050	2.69	0.097
5052	2.68	0.097
5056	2.64	0.095
5083	2.66	0.096
5086	2.65	0.096

5154	2.66	0.096
5357	2.70	0.098
5456	2.66	0.096
6061, 6063	2.70	0.098
6101, 6151	2.70	0.098
7075	2.80	0.101
7079	2.74	0.099
7178	2.82	0.102
Casting alloys		
242.0	2.81	0.102
295.0	2.81	0.102
356.0	2.68	0.097
380.0	2.76	0.099
413.0	2.66	0.096
443.0	2.69	0.097
514.0	2.65	0.096
520.0	2.57	0.093
Copper and copper alloys		
Wrought coppers		
Pure copper	8.96	0.324
Electrolytic tough pitch copper (ETP)	8.89	0.321

Deoxidized copper, high residual phosphorus (DHP)	8.94	0.323
Free-machining copper		
0.5% Te	8.94	0.323
1.0% Pb	8.94	0.323
Wrought alloys		
Gilding, 95%	8.86	0.320
Commercial bronze, 90%	8.80	0.318
Jewelry bronze, 87.5%	8.78	0.317
Red brass, 85%	8.75	0.316
Low brass, 80%	8.67	0.313
Cartridge brass, 70%	8.53	0.308
Yellow brass	8.47	0.306
Muntz metal	8.39	0.303
Leaded commercial bronze	8.83	0.319
Low-leaded brass (tube)	8.50	0.307
Medium-leaded brass	8.47	0.306
High-leaded brass (tube)	8.53	0.308
High-leaded brass	8.50	0.307
Extra-high-leaded brass	8.50	0.307
Free-cutting brass	8.50	0.307
Leaded Muntz metal	8.41	0.304

Forging brass	8.44	0.305
Architectural bronze	8.47	0.306
Inhibited admiralty	8.53	0.308
Naval brass	8.41	0.304
Leaded naval brass	8.44	0.305
Manganese bronze (A)	8.36	0.302
Phosphor bronze		
5% (A)	8.86	0.320
8% (C)	8.80	0.318
10% (D)	8.78	0.317
1.25%	8.89	0.321
Free-cutting phosphor bronze	8.89	0.321
Cupronickel		
30%	8.94	0.323
10%	8.94	0.323
Nickel silver		
65-18	8.73	0.315
55-18	8.70	0.314
High-silicon bronze (A)	8.53	0.308
Low-silicon bronze (B)	8.75	0.316
Aluminum bronze, 5% Al	8.17	0.294

Aluminum bronze (3)	7.78	0.281
Aluminum-silicon bronze	7.69	0.278
Aluminum bronze (1)	7.58	0.274
Aluminum bronze (2)	7.58	0.274
Beryllium copper	8.23	0.297
Casting alloys		
Chromium copper (1% Cr)	8.7	0.31
88Cu-10Sn-2Zn	8.7	0.31
88Cu-8Sn-4Zn	8.8	0.32
89Cu-11Sn	8.78	0.317
88Cu-6Sn-1.5Pb-4.5Zn	8.7	0.31
87Cu-8Sn-1Pb-4Zn	8.8	0.32
87Cu-10Sn-1Pb-2Zn	8.8	0.32
80Cu-10Sn-10Pb	8.95	0.323
83Cu-7Sn-7Pb-3Zn	8.93	0.322
85Cu-5Sn-9Pb-1Zn	8.87	0.320
78Cu-7Sn-15Pb	9.25	0.334
70Cu-5Sn-25Pb	9.30	0.336
85Cu-5Sn-5Pb-5Zn	8.80	0.318
83Cu-4Sn-6Pb-7Zn	8.6	0.31
81Cu-3Sn-7Pb-9Zn	8.7	0.31

76Cu-2.5Sn-6.5Pb-15Zn	8.77	0.317
72Cu-1Sn-3Pb-24Zn	8.50	0.307
67Cu-1Sn-3Pb-29Zn	8.45	0.305
61Cu-1Sn-1Pb-37Zn	8.40	0.304
Manganese bronze		
60 ksi	8.2	0.30
65 ksi	8.3	0.30
90 ksi	7.9	0.29
110 ksi	7.7	0.28
Aluminum bronze		
Alloy 9A	7.8	0.28
Alloy 9B	7.55	0.272
Alloy 9C	7.5	0.27
Alloy 9D	7.7	0.28
Nickel silver		
12% Ni	8.95	0.323
16% Ni	8.95	0.323
20% Ni	8.85	0.319
25% Ni	8.8	0.32
Silicon bronze	8.30	0.300
Silicon brass	8.30	0.300

Iron and iron alloys		
Pure iron	7.874	0.2845
Ingot iron	7.866	0.2842
Wrought iron	7.7	0.2
Gray cast iron	7.15[(a)]	0.258[(a)]
Malleable iron	7.27[(b)]	0.262[(b)]
Ductile iron	7.15	0.258
High-nickel iron (Ni-Resist)	7.5	0.271
High-chromium white iron	7.4	0.267
0.06% C steel	7.871	0.2844
0.23% C steel	7.859	0.2839
0.435% C steel	7.844	0.2834
1.22% C steel	7.830	0.2829
Low-carbon chromium-molybdenum steels		
0.5% Mo steel	7.86	0.283
1Cr-0.5Mo steel	7.86	0.283
1.25Cr-0.5Mo steel	7.86	0.283
2.25Cr-1.0Mo steel	7.86	0.283
5Cr-0.5Mo steel	7.78	0.278
7Cr-0.5Mo steel	7.78	0.278
9Cr-1Mo steel	7.67	0.276

Medium-carbon alloy steels		
1Cr-0.35Mo-0.25V steel	7.86	0.283
H11 die steel (5Cr-1.5Mo-0.4V)	7.75	0.280
Other iron-base alloys		
A-286	7.91	0.286
16-25-6 alloy	8.08	0.292
RA-330	8.03	0.290
Incoloy 800	7.95	0.287
Incoloy 901	8.23	0.297
T1 tool steel	8.67	0.313
M2 tool steel	8.16	0.295
W1 tool steel	7.84	0.282
O6 tool steel	7.70	0.277
A2 tool steel	7.86	0.284
H22 tool steel	8.36	0.302
L6 tool steel	7.86	0.284
P20 tool steel	7.85	0.284
20Cb3	8.08	0.292
20W-4Cr-2V-12Co steel	8.89	0.321
Invar (36% Ni)	8.00	0.289
Hipernik (50% Ni)	8.25	0.298

4% Si	7.6	0.27
10.27% Si	6.97	0.252
Stainless steels and heat-resistant alloys		
Corrosion-resistant steel castings		
CA-15	7.612	0.2750
CA-40	7.612	0.2750
CB-30	7.53	0.272
CC-50	7.53	0.272
CE-30	7.67	0.277
CF-8	7.75	0.280
CF-20	7.75	0.280
CF-8M, CF-12M	7.75	0.280
CF-8C	7.75	0.280
CF-16F	7.75	0.280
CH-20	7.72	0.279
CK-20	7.75	0.280
CN-7M	8.00	0.289
Heat-resistant alloy castings		
HA	7.72	0.279
HC	7.53	0.272
HD	7.58	0.274

HE	7.67	0.277
HF	7.75	0.280
HH	7.72	0.279
HI	7.72	0.279
HK	7.75	0.280
HL	7.72	0.279
HN	7.83	0.283
HT	7.92	0.286
HU	8.04	0.290
HW	8.14	0.294
HX	8.14	0.294
Wrought stainless and heat-resistant steels		
Type 301	7.9	0.29
Type 302	7.9	0.29
Type 302B	8.0	0.29
Type 303	7.9	0.29
Type 304	7.9	0.29
Type 305	8.0	0.29
Type 308	8.0	0.29
Type 309	7.9	0.29
Type 310	7.9	0.29

Type 314	7.72	0.279
Type 316	8.0	0.29
Type 317	8.0	0.29
Type 321	7.9	0.29
Type 347	8.0	0.29
Type 403	7.7	0.28
Type 405	7.7	0.28
Type 410	7.7	0.28
Type 416	7.7	0.28
Type 420	7.7	0.28
Type 430	7.7	0.28
Type 430F	7.7	0.28
Type 431	7.7	0.28
Types 440A, 440B, 440C	7.7	0.28
Type 446	7.6	0.27
Type 501	7.7	0.28
Type 502	7.8	0.28
19-9DL	7.97	0.29
Precipitation-hardening stainless steels		
PH15-7Mo	7.804	0.2819
17-4 PH	7.8	0.28

17-7 PH	7.81	0.282
Nickel-base alloys		
D-979	8.27	0.299
Nimonic 80A	8.25	0.298
Nimonic 90	8.27	0.299
M-252	8.27	0.298
Inconel 600	8.41	0.304
Inconel "X" 550	8.30	0.300
Inconel 718	8.22	0.297
Inconel "713C"	7.913	0.2859
Waspaloy	8.23	0.296
René 41	8.27	0.298
Hastelloy alloy B	9.24	0.334
Hastelloy alloy C	8.94	0.323
Hastelloy alloy X	8.23	0.297
Udimet 500	8.07	0.291
GMR-235	8.03	0.290
CMSX-2	8.56	0.309
PWA 1484	8.95	0.323
Cobalt-chromium-nickel-base alloys		
N-155 (HS-95)	8.23	0.296

S-590	8.36	0.301
Cobalt-base alloys		
S-816	8.68	0.314
V-36	8.60	0.311
HS-25	9.13	0.330
HS-36	9.04	0.327
HS-31	8.61	0.311
HS-21	8.30	0.300
Molybdenum-base alloy		
Mo-0.5Ti	10.2	0.368
Lead and lead alloys		
Chemical lead (99.90+% Pb)	11.34	0.4097
Corroding lead (99.73+% Pb)	11.36	0.4104
Arsenical lead	11.34	0.4097
Calcium lead	11.34	0.4097
5-95 solder	11.0	0.397
20-80 solder	10.2	0.368
50-50 solder	8.89	0.321
Antimonial lead alloys		
1% antimonial lead	11.27	0.407
Hard lead		

96Pb-4Sb	11.04	0.399
94Pb-6Sb	10.88	0.393
8% antimonial lead	10.74	0.388
9% antimonial lead	10.66	0.385
Lead-base babbitt alloys		
Lead-base babbitt		
SAE 13	10.24	0.370
SAE 14	9.73	0.352
Alloy 8	10.04	0.363
Arsenical lead		
Babbitt (SAE 15)	10.1	0.365
"G" Babbitt	10.1	0.365
Magnesium and magnesium alloys		
Magnesium (99.8%)	1.738	0.06279
Casting alloys		
AM100A	1.81	0.065
AZ63A	1.84	0.066
AZ81A	1.80	0.065
AZ91A, B, C	1.81	0.065
AZ92A	1.82	0.066
HK31A	1.79	0.065

HZ32A	1.83	0.066
ZH42, ZH62A	1.86	0.067
ZK51A	1.81	0.065
ZE41A	1.82	0.066
EZ33A	1.83	0.066
EK30A	1.79	0.065
EK41A	1.81	0.065
Wrought alloys		
M1A	1.76	0.064
A3A	1.77	0.064
AZ31B	1.77	0.064
PE	1.76	0.064
AZ61A	1.80	0.065
AZ80A	1.80	0.065
ZK60A, B	1.83	0.066
ZE10A	1.76	0.064
HM21A	1.78	0.064
HM31A	1.81	0.065
Nickel and nickel alloys		
Nickel (99.95% Ni + Co)	8.902	0.322
Nickel 200	8.89	0.321

Nickel 270	8.89	0.321
Duranickel 301	8.26	0.298
Cast nickel	8.34	0.301
Monel 400	8.80	0.318
"K" Monel	8.47	0.306
"H" Monel (cast)	8.5	0.31
"S" Monel (cast)	8.36	0.302
Inconel 625	8.44	0.305
Nickel-molybdenum-chromium-iron alloys		
Hastelloy B	9.24	0.334
Hastelloy C	8.94	0.323
Hastelloy D	7.8	0.282
Hastelloy F	8.17	0.295
Hastelloy N	8.79	0.317
Hastelloy W	9.03	0.326
Hastelloy X	8.23	0.297
Nickel-chromium-molybdenum-copper alloys		
Illium G	8.58	0.310
Illium R	8.58	0.310
Electrical resistance alloys		
80Ni-20Cr	8.4	0.30

60Ni-24Fe-16Cr	8.247	0.298
35Ni-45Fe-20Cr	7.95	0.287
Constantan	8.9	0.32
Tin and tin alloys		
Pure tin	7.3	0.264
Soft solder		
30% Pb	8.32	0.301
37% Pb	8.42	0.304
Tin babbitt		
Alloy 1	7.34	0.265
Alloy 2	7.39	0.267
Alloy 3	7.46	0.269
Alloy 4	7.53	0.272
Alloy 5	7.75	0.280
White metal	7.28	0.263
Pewter	7.28	0.263
Titanium and titanium alloys		
99.9% Ti	4.507	0.1628
99.2% Ti	4.507	0.1628
99.0% Ti	4.52	0.163
Ti-6Al-4V	4.43	0.160

Ti-5Al-2.5Sn	4.46	0.161
Ti-2Fe-2Cr-2Mo	4.65	0.168
Ti-8Mn	4.71	0.171
Ti-7Al-4Mo	4.48	0.162
Ti-4Al-4Mn	4.52	0.163
Ti-4Al-3Mo-1V	4.507	0.1628
Ti-2.5Al-16V	4.65	0.168
Zinc and zinc alloys		
Pure zinc	7.133	0.2577
AG40A alloy	6.6	0.24
AC41A alloy	6.7	0.24
Commercial rolled zinc		
0.08% Pb	7.14	0.258
0.06 Pb, 0.06 Cd	7.14	0.258
03 Pb, 0.3 Cd	7.14	0.258
Copper-hardened, rolled zinc, 1% Cu	7.18	0.259
Rolled zinc alloy, 1 Cu, 0.010 Mg	7.18	0.259
Zn-Cu-Ti alloy, 0.8 Cu, 0.15 Ti	7.18	0.259
Precious metals		
Silver	10.49	0.379
Gold	19.32	0.698

70Au-30Pt	19.92	. . .
Platinum	21.45	0.775
Pt-3.5Rh	20.9	. . .
Pt-5Rh	20.65	. . .
Pt-10Rh	19.97	. . .
Pt-20Rh	18.74	. . .
Pt-30Rh	17.62	. . .
Pt-40Rh	16.63	. . .
Pt-5Ir	21.49	. . .
Pt-10Ir	21.53	. . .
Pt-15Ir	21.57	. . .
Pt-20Ir	21.61	. . .
Pt-25Ir	21.66	. . .
Pt-30Ir	21.70	. . .
Pt-35Ir	21.79	. . .
Pt-5Ru	20.67	. . .
Pt-10Ru	19.94	. . .
Palladium	12.02	0.4343
60Pd-40Cu	10.6	0.383
95.5Pd-4.5Ru	12.07(a)	. . .
95.5Pd-4.5Ru	11.62(b)	. . .

Permanent magnet materials		
Cunico	8.30	0.300
Cunife	8.61	0.311
Comol	8.16	0.295
Alnico I	6.89	0.249
Alnico II	7.09	0.256
Alnico III	6.89	0.249
Alnico IV	7.00	0.253
Alnico V	7.31	0.264
Alnico VI	7.42	0.268
Barium ferrite	4.7	0.17
Vectolite	3.13	0.113
Pure metals		
Antimony	6.62	0.239
Beryllium	1.848	0.067
Bismuth	9.80	0.354
Cadmium	8.65	0.313
Calcium	1.55	0.056
Cesium	1.903	0.069
Chromium	7.19	0.260
Cobalt	8.85	0.322

Gallium	5.907	0.213
Germanium	5.323	0.192
Hafnium	13.1	0.473
Indium	7.31	0.264
Iridium	22.5	0.813
Lithium	0.534	0.019
Manganese	7.43	0.270
Mercury	13.546	0.489
Molybdenum	10.22	0.369
Niobium	8.57	0.310
Osmium	22.583	0.816
Plutonium	19.84	0.717
Potassium	0.86	0.031
Rhenium	21.04	0.756
Rhodium	12.44	0.447
Ruthenium	12.2	0.441
Selenium	4.79	0.174
Silicon	2.33	0.084
Silver	10.49	0.379
Sodium	0.97	0.035
Tantalum	16.6	0.600

Thallium	11.85	0.428
Thorium	11.72	0.423
Tungsten	19.3	0.697
Vanadium	6.1	0.22
Zirconium	6.5	0.23
Rare earth metals		
Cerium	8.23(c)	. . .
	6.66(d)	. . .
	6.77(e)	. . .
Dysprosium	8.55(f)	. . .
Erbium	9.15(f)	. . .
Europium	5.245(e)	. . .
Gadolinium	7.86(f)	. . .
Holmium	6.79(f)	. . .
Lanthanum	6.19(d)	. . .
	6.18(c)	. . .
	5.97(e)	. . .
Lutetium	9.85(f)	. . .
Neodymium	7.00(d)	. . .
	6.80(e)	. . .
Praseodymium	6.77(d)	. . .

	6.64[e]	. . .
Samarium	7.49[g]	. . .
Scandium	2.99[f]	. . .
Terbium	8.25[f]	. . .
Thulium	9.31[f]	. . .
Ytterbium	6.96[c]	. . .
Yttrium	4.47[f]	. . .
Actinide metals		
Actinium	10.1	0.3648
Berkelium	14.78	0.5339
Californium	15.10	0.5455
Curium	7	0.3
Einsteinium	8.84	0.3194

(a) 6.95 to 7.35 g/cm^3 (0.251 to 0.265 lb/in.^{3}).

(b) 7.20 to 7.34 g/cm^3 (0.260 to 0.265 lb/in.^{3}).

(c) Face-centered cubic.

(d) Hexagonal.

(e) Body-centered cubic.

(f) Close-packed hexagonal.

(g) Rhombohedral

Table 2 Linear thermal expansion of metals and alloys

Metal or alloy	**Temperature, °C**	**Coefficient of expansion, µin./in. · °C**
Aluminum and aluminum alloys		
Aluminum (99.996%)	20-100	23.6
Wrought alloys		
EC, 1060, 1100	20-100	23.6
2011, 2014	20-100	23.0
2024	20-100	22.8
2218	20-100	22.3
3003	20-100	23.2
4032	20-100	19.4
5005, 5050, 5052	20-100	23.8
5056	20-100	24.1
5083	20-100	23.4
5086	60-300	23.9
5154	20-100	23.9
5357	20-100	23.7
5456	20-100	23.9
6061, 6063	20-100	23.4
6101, 6151	20-100	23.0
7075	20-100	23.2

7079, 7178	20-100	23.4
Casting alloys		
242.0	20-100	22.5
295.0	20-100	22.9
356.0	20-100	21.4
380.0	20-100	21.2
413.0	20-100	20.5
443.0	20-100	22.1
514.0	20-100	23.9
520.0	20-100	25.2
Copper and copper alloys		
Wrought coppers		
Pure copper	20	16.5
Electrolytic tough pitch copper (ETP)	20-100	16.8
Deoxidized copper, high residual phosphorus (DHP)	20-300	17.7
Oxygen-free copper	20-300	17.7
Free-machining copper, 0.5% Te or 1% Pb	20-300	17.7
Wrought alloys		
Gilding, 95%	20-300	18.1
Commercial bronze, 90%	20-300	18.4
Jewelry bronze, 87.5%	20-300	18.6

Red brass, 85%	20-300	18.7
Low brass, 80%	20-300	19.1
Cartridge brass, 70%	20-300	19.9
Yellow brass	20-300	20.3
Muntz metal	20-300	20.8
Leaded commercial bronze	20-300	18.4
Low-leaded brass	20-300	20.2
Medium-leaded brass	20-300	20.3
High-leaded brass	20-300	20.3
Extra-high-leaded brass	20-300	20.5
Free-cutting brass	20-300	20.5
Leaded Muntz metal	20-300	20.8
Forging brass	20-300	20.7
Architectural bronze	20-300	20.9
Inhibited admiralty	20-300	20.2
Naval brass	20-300	21.2
Leaded naval brass	20-300	21.2
Manganese bronze (A)	20-300	21.2
Phosphor bronze		
5% (A)	20-300	17.8
8% (C)	20-300	18.2

10% (D)	20-300	18.4
1.25%	20-300	17.8
Free-cutting phosphor bronze	20-300	17.3
Cupronickel		
30%	20-300	16.2
10%	20-300	17.1
Nickel silver		
65-18	20-300	16.2
55-18	20-300	16.7
65-12	20-300	16.2
High-silicon bronze(a)	20-300	18.0
Low-silicon bronze(b)	20-300	17.9
Aluminum bronze (3)	20-300	16.4
Aluminum-silicon bronze	20-300	18.0
Aluminum bronze (1)	20-300	16.8
Beryllium copper	20-300	17.8
Casting alloys		
88Cu-8Sn-4Zn	21-177	18.0
89Cu-11Sn	20-300	18.4
88Cu-6Sn-1.5Pb-4.5Zn	21-260	18.5
87Cu-8Sn-1Pb-4Zn	21-177	18.0

87Cu-10Sn-1Pb-2Zn	21-177	18.0
80Cu-10Sn-10Pb	21-204	18.5
78Cu-7Sn-15Pb	21-204	18.5
85Cu-5Sn-5Pb-5Zn	21-204	18.1
72Cu-1Sn-3Pb-24Zn	21-93	20.7
67Cu-1Sn-3Pb-29Zn	21-93	20.2
61Cu-1Sn-1Pb-37Zn	21-260	21.6
Manganese bronze		
60 ksi	21-204	20.5
65 ksi	21-93	21.6
110 ksi	21-260	19.8
Aluminum bronze		
Alloy 9A	. . .	17
Alloy 9B	20-250	17
Alloys 9C, 9D	. . .	16.2
Iron and iron alloys		
Pure iron	20	11.7
Fe-C alloys		
0.06% C	20-100	11.7
0.22% C	20-100	11.7
0.40% C	20-100	11.3

0.56% C	20-100	11.0
1.08% C	20-100	10.8
1.45% C	20-100	10.1
Invar (36% Ni)	20	2.0
13Mn-1.2C	20	18.0
13Cr-0.35C	20-100	10.0
12.3Cr-0.4Ni-0.09C	20-100	9.8
17.7Cr-9.6Ni-0.06C	20-100	16.5
18W-4Cr-1V	0-100	11.2
Gray cast iron	0-100	10.5
Malleable iron (pearlitic)	20-400	12
Lead and lead alloys		
Corroding lead (99.73 + % Pb)	17-100	29.3
5-95 solder	15-110	28.7
20-80 solder	15-110	26.5
50-50 solder	15-110	23.4
1% antimonial lead	20-100	28.8
Hard lead		
96Pb-6Sb	20-100	28.8
94Pb-6Sb	20-100	27.2
8% antimonial lead	20-100	26.7

9% antimonial lead	20-100	26.4
Lead-base babbitt		
SAE 14	20-100	19.6
Alloy 8	20-100	24.0
Magnesium and magnesium alloys		
Magnesium (99.8%)	20	25.2
Casting alloys		
AM100A	18-100	25.2
AZ63A	20-100	26.1
AZ91A, B, C	20-100	26
AZ92A	18-100	25.2
HZ32A	20-200	26.7
ZH42	20-200	27
ZH62A	20-200	27.1
ZK51A	20	26.1
EZ33A	20-100	26.1
EK30A, EK41A	20-100	26.1
Wrought alloys		
M1A, A3A	20-100	26
AZ31B, PE	20-100	26
AZ61A, AZ80A	20-100	26

ZK60A, B	20-100	26
HM31A	20-93	26.1
Nickel and nickel alloys		
Nickel (99.95% Ni + Co)	0-100	13.3
Duranickel	0-100	13.0
Monel	0-100	14.0
Monel (cast)	25-100	12.9
Inconel	20-100	11.5
Ni-o-nel	27-93	12.9
Hastelloy B	0-100	10.0
Hastelloy C	0-100	11.3
Hastelloy D	0-100	11.0
Hastelloy F	20-100	14.2
Hastelloy N	21-204	10.4
Hastelloy W	23-100	11.3
Hastelloy X	26-100	13.8
Illium G	0-100	12.19
Illium R	0-100	12.02
80Ni-20Cr	20-1000	17.3
60Ni-24Fe-16Cr	20-1000	17.0
35Ni-45Fe-20Cr	20-500	15.8

Constantan	20-1000	18.8
Tin and tin alloys		
Pure tin	0-100	23
Solder		
70Sn-30Pb	15-110	21.6
63Sn-37Pb	15-110	24.7
Titanium and titanium alloys		
99.9% Ti	20	8.41
99.0% Ti	93	8.55
Ti-5Al-2.5Sn	93	9.36
Ti-8Mn	93	8.64
Zinc and zinc alloys		
Pure zinc	20-250	39.7
AG40A alloy	20-100	27.4
AC41A alloy	20-100	27.4
Commercial rolled zinc		
0.08 Pb	20-40	32.5
0.3 Pb, 0.3 Cd	20-98	33.9(a)
Rolled zinc alloy, 1 Cu, 0.010 Mg	20-100	34.8(b)
Zn-Cu-Ti alloy, 0.8 Cu, 0.15 Ti	20-100	24.9(c)
Pure metals		

Beryllium	25-100	11.6
Cadmium	20	29.8
Calcium	0-400	22.3
Chromium	20	6.2
Cobalt	20	13.8
Gold	20	14.2
Iridium	20	6.8
Lithium	20	56
Manganese	0-100	22
Palladium	20	11.76
Platinum	20	8.9
Rhenium	20-50	6.7
Rhodium	20-100	8.3
Ruthenium	20	9.1
Silicon	0-1400	5
Silver	0-100	19.68
Tungsten	27	4.6
Vanadium	23-100	8.3
Zirconium	. . .	5.85

(a) Longitudinal; 23.4 transverse.

(b) Longitudinal; 21.1 transverse.

(c) Longitudinal; 19.4 transverse

Table 3 Thermal conductivity of metals and alloys

Metal or alloy	Thermal conductivity near room temperature, cal/cm^2 · cm · s · °C
Aluminum and aluminum alloys	
Wrought alloys	
EC (O)	0.57
1060 (O)	0.56
1100	0.53
2011 (T3)	0.34
2014 (O)	0.46
2024 (L)	0.45
2218 (T72)	0.37
3003 (O)	0.46
4032 (O)	0.37
5005	0.48
5050 (O)	0.46
5052 (O)	0.33
5056 (O)	0.28
5083	0.28

5086	0.30
5154	0.30
5357	0.40
5456	0.28
6061 (O)	0.41
6063 (O)	0.52
6101 (T6)	0.52
6151 (O)	0.49
7075 (T6)	0.29
7079 (T6)	0.29
7178	0.29
Casting alloys	
242.0 (T77, sand)	0.36
295.0 (T4, sand)	0.33
356.0 (T51, sand)	0.40
380.0 (F, die)	0.26
413.0 (F, die)	0.37
443.0 (F, sand)	0.35
514.0 (F, sand)	0.33
520.0 (T4, sand)	0.21
Copper and copper alloys	

Wrought coppers	
Pure copper	0.941
Electrolytic tough pitch copper (ETP)	0.934
Deoxidized copper, high residual phosphorus (DHP)	0.81
Free-machining copper	
0.5% Te	0.88
1% Pb	0.92
Wrought alloys	
Gilding, 95%	0.56
Commercial bronze, 90%	0.45
Jewelry bronze, 87.5%	0.41
Red brass, 85%	0.38
Low brass, 80%	0.33
Cartridge brass, 70%	0.29
Yellow brass	0.28
Muntz metal	0.29
Leaded-commercial bronze	0.43
Low-leaded brass (tube)	0.28
Medium-leaded brass	0.28
High-leaded brass (tube)	0.28
High-leaded brass	0.28

Extra-high-leaded brass	0.28
Leaded Muntz metal	0.29
Forging brass	0.28
Architectural bronze	0.29
Inhibited admiralty	0.26
Naval brass	0.28
Leaded naval brass	0.28
Manganese bronze (A)	0.26
Phosphor bronze	
5% (A)	0.17
8% (C)	0.15
10% (D)	0.12
1.25%	0.49
Free-cutting phosphor bronze	0.18
Cupronickel	
30%	0.07
10%	0.095
Nickel silver	
65-18	0.08
55-18	0.07
65-12	0.10

High-silicon bronze (A)	0.09
Low-silicon bronze (B)	0.14
Aluminum bronze, 5% Al	0.198
Aluminum bronze (3)	0.18
Aluminum-silicon bronze	0.108
Aluminum bronze (1)	0.144
Aluminum bronze (2)	0.091
Beryllium copper	0.20(a)
Casting alloys	
Chromium copper (1% Cr)	0.4(a)
89Cu-11Sn	0.121
88Cu-6Sn-1.5Pb-4.5Zn	(b)
87Cu-8Sn-1Pb-4Zn	(c)
87Cu-10Sn-1Pb-2Zn	(c)
80Cu-10Sn-10Pb	(c)
Manganese bronze, 110 ksi	(d)
Aluminum bronze	
Alloy 9A	(e)
Alloy 9B	(f)
Alloy 9C	(b)
Alloy 9D	(c)

Propeller bronze	(g)
Nickel silver	
12% Ni	(h)
16% Ni	(h)
20% Ni	(i)
25% Ni	(j)
Silicon bronze	(h)
Iron and iron alloys	
Pure iron	0.178
Cast iron (3.16 C, 1.54 Si, 0.57 Mn)	0.112
Carbon steel	
0.23 C, 0.64 Mn	0.124
1.22 C, 0.35 Mn	0.108
Alloy steel (0.34 C, 0.55 Mn, 0.78 Cr, 3.53 Ni, 0.39 Mo, 0.05 Cu)	0.079
Type 410	0.057
Type 304	0.036
T1 tool steel	0.058
Lead and lead alloys	
Corroding lead (99.73 + % Pb)	0.083
5-95 solder	0.085
20-80 solder	0.089

50-50 solder	0.111
1% antimonial lead	0.080
Hard lead	
96Pb-4Sb	0.073
94Pb-6Sb	0.069
8% antimonial lead	0.065
9% antimonial lead	0.064
Lead-base babbitt	
SAE 14	0.057
Alloy 8	0.058
Magnesium and magnesium alloys	
Magnesium (99.8%)	0.367
Casting alloys	
AM100A	0.17
AZ63A	0.18
AZ81A (T4)	0.12
AZ91A, B, C	0.17
AZ92A	0.17
HK31A (T6, sand cast)	0.22
HZ32A	0.26
ZH42	0.27

ZH62A	0.26
ZK51A	0.26
ZE41A (T5)	0.27
EZ33A	0.24
EK30A	0.26
EK41A (T5)	0.24
Wrought alloys	
M1A	0.33
AZ31B	0.23
AZ61A	0.19
AZ80A	0.18
ZK60A, B (F)	0.28
ZE10A (O)	0.33
HM21A (O)	0.33
HM31A	0.25
Nickel and nickel alloys	
Nickel (99.95% Ni + Co)	0.22
"A" nickel	0.145
"D" nickel	0.115
Monel	0.062
"K" Monel	0.045

Inconel	0.036
Hastelloy B	0.027
Hastelloy C	0.03
Hastelloy D	0.05
Illium G	0.029
Illium R	0.031
60Ni-24Fe-16Cr	0.032
35Ni-45Fe-20Cr	0.031
Constantan	0.051
Tin and tin alloys	
Pure tin	0.15
Soft solder (63Sn-37Pb)	0.12
Tin foil (92Sn-8Zn)	0.14
Titanium and titanium alloys	
Titanium (99.0%)	0.043
Ti-5Al-2.5Sn	0.019
Ti-2Fe-2Cr-2Mo	0.028
Ti-8Mn	0.026
Zinc and zinc alloys	
Pure zinc	0.27
AG40A alloy	0.27

AC41A alloy	0.26
Commercial rolled zinc	
0.08 Pb	0.257
0.06 Pb, 0.06 Cd	0.257
Rolled zinc alloy (1 Cu, 0.010 Mg)	0.25
Zn-Cu-Ti alloy (0.8 Cu, 0.15 Ti)	0.25
Pure metals	
Beryllium	0.35
Cadmium	0.22
Chromium	0.16
Cobalt	0.165
Germanium	0.14
Gold	0.71
Indium	0.057
Iridium	0.14
Lithium	0.17
Molybdenum	0.34
Niobium	0.13
Palladium	0.168
Platinum	0.165
Plutonium	0.020

Rhenium	0.17
Rhodium	0.21
Silicon	0.20
Silver	1.0
Sodium	0.32
Tantalum	0.130
Thallium	0.093
Thorium	0.090
Tungsten	0.397
Uranium	0.071
Vanadium	0.074
Yttrium	0.035

(a) Depends on processing.

(b) 18% of Cu.

(c) 12% of Cu.

(d) 9.05% of Cu.

(e) 15% of Cu.

(f) 16% of Cu.

(g) 11% of Cu.

(h) 7% of Cu.

(i) 6% of Cu.

(j) 6.5% of Cu

Table 4 Electrical conductivity and resistivity of metals and alloys

Metal or alloy	**Conductivity, % IACS**	**Resistivity, μΩ· cm**
Aluminum and aluminum alloys		
1100 (O)	59	2.9
2024 (O)	50	3.4
3003 (O)	50	3.4
4032 (O)	40	4.3
5052 (all)	35	4.9
5056 (O)	29	5.9
6061 (T6)	43	4.0
6101 (T6)	57	3.0
7075 (O)	45	3.8
7075 (T6)	33	5.2
Copper and copper alloys		
Wrought copper		
Pure copper	103.06	1.67
Electrolytic tough pitch copper (ETP)	101	1.71
Oxygen-free copper (OF)	101	1.71
Free-machining copper		

0.5% Te	95	1.82
1.0% Pb	98	1.76
Wrought alloys		
Cartridge brass, 70%	28	6.2
Yellow brass	27	6.4
Leaded commercial bronze	42	4.1
Phosphor bronze, 1.25%	48	3.6
Nickel silver, 55-18	5.5	31
Low-silicon bronze (B)	12	14.3
Beryllium copper	22-30(a)	5.7-7.8(a)
Casting alloys		
Chromium copper (1% Cr)	80-90(a)	2.10
88Cu-8Sn-4Zn	11	15
87Cu-10Sn-1Pb-2Zn	11	15
Electrical contact materials		
Copper alloys		
0.04 oxide	100	1.72
1.25 Sn + P	48	3.6
5 Sn + P	18	11
8 Sn + P	13	13
15 Zn	37	4.7

20 Zn	32	5.4
35 Zn	27	6.4
2 Be + Ni or Co(b)	17-21	9.6-11.5
Silver and silver alloys		
Fine silver	104	1.59
92.5Ag-7.5Cu	88	2
90Ag-10Cu	85	2
72Ag-28Cu	87	2
72Ag-26Cu-2Ni	60	2.9
85Ag-15Cd	35	4.93
97Ag-3Pt	45	3.5
97Ag-3Pd	58	2.9
90Ag-10Pd	27	5.3
90Ag-10Au	40	4.2
60Ag-40Pd	8	23
70Ag-30Pd	12	14.3
Platinum and platinum alloys		
Platinum	16	10.6
95Pt-5Ir	9	19
90Pt-10Ir	7	25
85Pt-15Ir	6	28.5

80Pt-20Ir	5.6	31
75Pt-25Ir	5.5	33
70Pt-30Ir	5	35
65Pt-35Ir	5	36
95Pt-5Ru	5.5	31.5
90Pt-10Ru	4	43
89Pt-11Ru	4	43
86Pt-14Ru	3.5	46
96Pt-4W	5	36
Palladium and palladium alloys		
Palladium	16	10.8
95.5Pd-4.5Ru	7	24.2
90Pd-10Ru	6.5	27
70Pd-30Ag	4.3	40
60Pd-40Ag	4.0	43
50Pd-50Ag	5.5	31.5
72Pd-26Ag-1.71-2Ni	4	43
60Pd-40Cu	5	35(c)
45Pd-30Ag-20Au-5Pt	4.5	39
35Pd-30Ag-14Cu-10Pt-10Au-1Zn	5	35
Gold and gold alloys		

Gold	75	2.35
90Au-10Cu	16	10.8
75Au-25Ag	16	10.8
72.5Au-14Cu-8.5Pt-4Ag-1Zn	10	17
69Au-25Ag-6Pt	11	15
41.7Au-32.5Cu-18.8Ni-7Zn	4.5	39
Electrical heating alloys		
Ni-Cr and Ni-Cr-Fe alloys		
78.5Ni-20Cr-1.5Si (80-20)	1.6	108.05
73.5Ni-20Cr-5Al-1.5Si	1.2	137.97
68Ni-20Cr-8.5Fe-2Si	1.5	116.36
60Ni-16Cr-22.5Fe-1.5Si	1.5	112.20
35Ni-20Cr-43.5Fe-1.5Si	1.7	101.4
Fe-Cr-Al alloys		
72Fe-23Cr-5Al	1.3	138.8
55Fe-37.5Cr-7.5Al	1.2	166.23
Pure metals		
Molybdenum	34	5.2
Platinum	16	10.64
Tantalum	13.9	12.45
Tungsten	30	5.65

Nonmetallic heating element materials		
Silicon carbide (SiC)	1-1.7	100-200
Molybdenum disilicide ($MoSi_2$)	4.5	37.24
Graphite	. . .	910.1
Instrument and control alloys		
Cu-Ni alloys		
98Cu-2Ni	35	4.99
94Cu-6Ni	17	9.93
89Cu-11Ni	11	14.96
78Cu-22Ni	5.7	29.92
55Cu-45Ni (constantan)	3.5	49.87
Cu-Mn-Ni alloys		
87Cu-13Mn (manganin)	3.5	48.21
83Cu-13Mn-4Ni (manganin)	3.5	48.21
85Cu-10Mn-4Ni (shunt manganin)	4.5	38.23
70Cu-20Ni-10Mn	3.6	48.88
67Cu-5Ni-27Mn	1.8	99.74
Nickel-base alloys		
99.8 Ni	23	7.98
71Ni-29Fe	9	19.95
80Ni-20Cr	1.5	112.2

75Ni-20Cr-3Al + Cu or Fe	1.3	132.98
76Ni-17Cr-4Si-3Mn	1.3	132.98
60Ni-16Cr-24Fe	1.5	112.2
35Ni-20Cr-45Fe	1.7	101.4
Fe-Cr-Al alloy		
72Fe-23Cr-5Al-0.5Co	1.3	135.48
Pure metals		
Iron (99.99%)	17.75	9.71
Thermostat metals		
75Fe-22Ni-3Cr	3	78.13
72Mn-18Cu-10Ni	1.5	112.2
67Ni-30Cu-1.4Fe-1Mn	3.5	56.52
75Fe-22Ni-3Cr	12	15.79
66.5Fe-22Ni-8.5Cr	3.3	58.18
Permanent magnet materials		
Carbon steel		
0.65% C	9.5	18
1% C	8	20
Chromium steel, 3.5% Cr	6.1	29
Tungsten steel, 6% W	6	30
Cobalt steel		

17% Co	6.3	28
36% Co	6.5	27
Intermediate alloys		
Cunico	7.5	24
Cunife	9.5	18
Comol	3.6	45
Alnico alloys		
Alnico I	3.3	75
Alnico II	3.3	65
Alnico III	3.3	60
Alnico IV	3.3	75
Alnico V	3.5	47
Alnico VI	3.5	50
Magnetically soft materials		
Electrical steel sheet		
M-50	9.5	18
M-43	6-9	20-28
M-36	5.5-7.5	24-33
M-27	3.5-5.5	32-47
M-22	3.5-5	41-52
M-19	3.5-5	41-56

M-17	3-3.5	45-58
M-15	3-3.5	45-69
M-14	3-3.5	58-69
M-7	3-3.5	45-52
M-6	3-3.5	45-52
M-5	3-3.5	45-52
Moderately high-permeability materials(d)		
Thermenol	0.5	162
16 Alfenol	0.7	153
Sinimax	2	90
Monimax	2.5	80
Supermalloy	3	65
4-79 Moly Permalloy, Hymu 80	3	58
Mumetal	3	60
1040 alloy	3	56
High Permalloy 49, A-L 4750, Armco 48	3.6	48
45 Permalloy	3.6	45
High-permeability materials(e)		
Supermendur	4.5	40
2V Permendur	4.5	40
35% Co, 1% Cr	9	20

Ingot iron	17.5	10
0.5% Si steel	6	28
1.75% Si steel	4.6	37
3.0% Si steel	3.6	47
Grain-oriented 3.0% Si steel	3.5	50
Grain-oriented 50% Ni iron	3.6	45
50% Ni iron	3.5	50
Relay steels and alloys after annealing		
Low-carbon iron and steel		
Low-carbon iron	17.5	10
1010 steel	14.5	12
Silicon steels		
1% Si	7.5	23
2.5% Si	4	41
3% Si	3.5	48
3% Si, grain-oriented	3.5	48
4% Si	3	59
Stainless steels		
Type 410	3	57
Type 416	3	57
Type 430	3	60

Type 443	3	68
Type 446	3	61
Nickel irons		
50% Ni	3.5	48
78% Ni	11	16
77% Ni (Cu, Cr)	3	60
79% Ni (Mo)	3	58
Stainless and heat-resistant alloys		
Type 302	3	72
Type 309	2.5	78
Type 316	2.5	74
Type 317	2.5	74
Type 347	2.5	73
Type 403	3	57
Type 405	3	60
Type 501	4.5	40
HH	2.5	80
HK	2	90
HT	1.7	100

(a) Precipitation hardened; depends on processing.

(b) A heat treatable alloy.

(c) Annealed and quenched.

(d) At low field strength and high electrical resistance.

(e) At higher field strength; annealed for optimal magnetic properties

Table 5 Approximate melting temperatures of metals and alloys

Metal or alloy	**Temperature**	
	°C	**°F**
Aluminum and aluminum alloys		
Wrought alloys		
1100	655	1215
2017	640	1185
Alclad 2024	635	1180
3003	655	1210
5052	650	1200
6061	650	1205
7075	635	1175
Casting alloys		
242.0	635	1175
295.0	645	1190
336.0	565	1050
A380.0	595	1100

413.0	580	1080
B443.0	630	1170
514.0	640	1185
520.0	605	1120
Copper and copper alloys		
Wrought copper and copper alloys		
Pure copper	1080	1980
Beryllium copper		
1.7% Be, 0.25% Co	870-980	1600-1800
1.9% Be, 0.25% Co	870-980	1600-1800
Red brass, 15% Zn	1025	1880
Cartridge brass, 30% Zn	955	1750
Yellow brass	930	1710
Muntz metal	905	1660
Admiralty brass	940	1720
Naval brass	900	1650
Phosphor bronze		
5% Sn	1050	1920
10% Sn	1000	1830
Aluminum bronze, 7% Al, 2.5% Fe	1045	1915
High-silicon bronze, 3.3% Si	1025	1880

Copper-nickel		
10% Ni	1150	2100
21% Ni	1150-1200	2100-2190
30% Ni	1240	2260
Nickel-silver		
72-18	1150	2100
65-18	1110	2030
55-18	1055	1930
Casting alloys		
85Cu-5Zn-5Sn-5Pb	1005	1840
G bronze, 10% Sn, 2% Zn	980	1800
M bronze, 8.5% Sn, 4% Zn	1000	1832
83Cu-7Sn-7Pb-3Zn	980	1800
Nickel-tin bronze (A)	1025	1880
Nickel-tin bronze (B)	1025	1880
Nickel-aluminum bronze	1045-1060	1910-1940
Copper nickel		
10% Ni	1150	2100
30% Ni	1240	2260
Nickel-silver		
12% Ni	1000	1830

20% Ni	1145	2090
25% Ni	1045	1910
Low-melting-point metals and alloys		
55.5Bi-44.5Pb	125	255
58Bi-42Sn	138	281
50Bi-26.7Pb-13.3Sn-10Cd	70	158
44.7Bi-22.6Pb-19.1In-5.3Cd-8.3Sn	47	117
Lead, 99.9% min Pb	327	621
Antimonial lead, 10% Sb	285	545
Tellurium lead, 0.04% Te, 0.06% Cu	327	621
50-50 lead-tin solder	216	421
60-40 tin-lead solder	190	374
Tin, 99.8% min Sn	232	449
Zinc and zinc alloys		
Rolled zinc		
0.08% Pb	419	786
1% Cu, 0.01% Mg	422	792
AG40A	387	728
AC41A	386	727
Magnesium and magnesium alloys		
Casting alloys		

AZ91B	595	1105
AZ91C	595	1105
AZ92A	593	1100
EZ33A	643	1189
HZ32A	648	1198
Wrought alloys		
AZ31B	630	1170
AZ80A	610	1130
HK31A	651	1204
ZK60A	635	1175
Titanium and titanium alloys		
Unalloyed titanium		
ASTM grade 1	1683	3063
ASTM grade 2	1704	3100
ASTM grade 4	1670	3038
Ti-0.2Pd	1704	3100
Ti-5Al-2.5Sn	1650	3002
Ti-6Al-2Sn-4Zr-2Mo	1650	3000
Ti-6Al-6V-2Sn	1705	3100
Ti-6Al-4V	1650	3000
Ti-6Al-2Sn-4Zr-6Mo	1675	3050

Nickel and nickel alloys		
Low-alloy nickels and nickel-coppers		
Nickel 200, 201, and 205, 99.5% min Ni	1445	2635
Nickel 211, 95% Ni, 4.9% Mn, 0.1% C	1425	2600
Nickel 270, 99.98% min Ni	1455	2650
Duranickel 301	1440	2620
Nickel-beryllium, 2.7% Be	1265	2310
Monel alloy 400	1350	2460
Monel alloy R-405	1350	2460
Monel alloy K-500	1350	2460
"S" Monel (cast)	1290	2350
Nickel-chromium-iron alloys		
Inconel alloy 600	1415	2575
Inconel alloy 601	1370	2494
Inconel alloy 617	1375	2510
Inconel alloy 625	1350	2460
Inconel alloy 690	1375	2510
Inconel alloy 718	1335	2437
Inconel alloy X-750	1425	2600
Inconel alloy 751	1425	2600
Nickel-chromium alloys		

Nimonic alloy 75	1380	2515
Nimonic alloy 80A	1370	2500
Nimonic alloy 90	1370	2500
Nimonic alloy 115	1315	2400
Nickel-chromium-molybdenum alloys		
Hastelloy alloy C-276	1370	2500
Hastelloy alloy G	1345	2450
Hastelloy alloy N	1400	2550
Hastelloy alloy S	1380	2516
Hastelloy alloy W	1315	2400
Hastelloy alloy X	1355	2470
Chlorimet 2 and 3	1315	2400
High-temperature high-strength alloys		
Incoloy alloy 800	1385	2525
Incoloy alloy 801	1385	2525
Incoloy alloy 802	1370	2500
Incoloy alloy 825	1400	2550
Alloy 713C (casting)	1290	2350
Alloy 713LC	1320	2410
A-286	1400	2550
IN-100	1335	2435

IN-102	1290	2350
IN-738	1230-1315	2250-2400
IN-939	1230-1340	2255-2444
Alloy 25 (L-605)	1410	2570
Alloy 188	1330	2425
MAR-M 246	1355	2475
M-252	1370	2500
René 41	1370	2500
TD nickel	1455	2650
Udimet alloy 500	1395	2540
Udimet alloy 700	1400	2550
Waspaloy	1355	2475
B-1900	1300	2375
Multimet alloy N-155	1355	2470
Discaloy	1465	2665
Irons and steels		
Irons		
Ingot iron	1535	2795
Wrought iron	1510	2750
Gray cast iron	1175	2150
Malleable iron	1230	2250

Ductile iron	1175	2150
Ni-Resists (15.5-35% Ni)	1230	2250
Duriron (14.5% Si)	1260	2300
Steels		
Carbon steel (SAE 1020)	1515	2760
4340 steel	1505	2740
9% Ni steel	1500	2730
Maraging steels (18Ni-200)	1455	2650
Wrought stainless steels		
Type 201	1400-1450	2550-2650
Type 304	1400-1450	2550-2650
Type 316	1375-1400	2500-2550
Type 405	1480-1530	2700-2790
Type 409	1480-1530	2700-2790
Type 420	1450-1510	2650-2750
Type 430	1425-1510	2600-2750
Type 440C	1370-1480	2500-2700
Type 446	1425-1510	2600-2750
17-4 PH	1400-1440	2560-2625
AM 350	1400	2550
Cast stainless steels		

Corrosion-resistant alloys		
CA-15	1510	2750
CA-40	1495	2725
CB-7Cu-1	1510	2750
CF-8	1425	2600
CF-3M	1400	2550
CF-20	1415	2575
CH-20	1425	2600
CN-7M	1455	2650
Heat-resistant alloys		
HA	1510	2750
HC	1495	2725
HD	1480	2700
HE	1455	2650
HF	1400	2550
HH	1370	2500
HK	1400	2550
HL	1425	2600
HN	1370	2500
HP, HT, and HU	1345	2450
HW AND HX	1290	2350

Refractory metals and alloys		
Niobium	2470	4475
Nb-1Zr	2400	4350
Molybdenum	2610	4730
Mo-0.5Ti	2610	4730
Tantalum	2995	5425
Tungsten	3410	6170
W-25Re	3100	5612
W-50Re	2550	4622
Precious metals and alloys		
Gold (99.995% min Au)	1063	1945
Silver (99.9% min Ag)	961	1761
BAg-1 (brazing alloy)	635	1175
Platinum	1791	3256
Palladium	1552	2826
Iridium	2443	4429
Rhodium	1960	3560
90Pt-10Ir	1782	3240
60Pd-40Ag	1338	2440

Table 6 Physical properties of common gases and liquids

Name	Formula	Molecular weight	Density, g/L[(a)]	Melting point, °C	Boiling point, °C	Auto-ignition point, °C	Explosive limits, percent by volume air

						point, °C	**Lower**	**Upper**
Acetylene	C_2H_2	26.04	1.173	-81	-83.6 subl.(c)	335	2.5	80.0
Air	. . .	28.97(b)	1.2929	. . .	. . .	. . .	. . .	. . .
Ammonia	NH_3	17.03	0.7710	-77.7	-33.4	780	16.0	27.0
Argon	Ar	39.94	1.784	-189.2	-185.7	. . .	. . .	. . .
Butane-*n*	C_4H_{10}	58.12	2.703	-138	-0.6	430	1.6	8.5
Butane-*i*	C_4H_{10}	58.12	2.637	-159	-11.7	. . .	. . .	. . .
Butylene-*n*	C_4H_8	56.10	2.591	-185	-6.3	. . .	1.7	9.0
Carbon dioxide	CO_2	44.01	1.977	-57 (at 5 atm)	-78.5 subl.(c)	. . .	. . .	. . .
Carbon monoxide	CO	28.01	1.250	-207	-191	650	12.5	74.2
Chlorine	Cl_2	70.91	3.214	-101	-34	. . .	. . .	. . .
Ethane	C_2H_6	30.07	1.356	-172	-88.6	510	3.1	15.0
Ethylene	C_2H_4	28.05	1.261	-169	-103.7	543	3.0	34.0
Helium	He	4.003	0.1785	-272	-268.9	. . .	. . .	. . .
Heptane-*n*	C_7H_{16}	100.20	0.684 g/cm^3	-90.6	98.4	233	1.0	6.0
Hexane-*n*	C_6H_{14}	86.17	0.6594 g/cm^3	-95.3	68.7	248	1.2	6.9
Hydrogen	H_2	2.016	0.0899	-259.2	-252.8	580	4.1	74.2
Hydrogen chloride	HCl	36.47	1.639	-112	-84	. . .	. . .	. . .
Hydrogen	HF	20.01	0.921	-92.3	19.5	. . .	. . .	. . .

fluoride								
Hydrogen sulfide	H_2S	34.08	1.539	-84	-62	. . .	4.3	45.5
Methane	CH_4	16.04	0.7168	-182.5	-161.5	538	5.3	13.9
Nitrogen	N_2	28.016	1.2506	-209.9	-195.8	. . .	. . .	. . .
Octane-*n*	C_8H_{18}	114.23	0.7025 g/cm^3	-56.8	125.7	232	0.8	3.2
Oxygen	O_2	32.00	1.4290	-218.4	-183.0	. . .	. . .	. . .
Pentane-*n*	C_5H_{12}	72.15	0.016 g/cm^3	-131	36.2	310	1.4	8.0
Propane	C_3H_8	44.09	2.020	-189	-44.5	465	2.4	9.5
Propylene	C_3H_6	42.05	1.915	-184	-48	458	2.0	11.1
Sulfur dioxide	SO_2	64.06	2.926	-75.7	-10.0	. . .	. . .	. . .

Source: *Corrosion Tests and Standards: Application and Interpretation,* ASTM, 1995, p 27

(a) Density of gases is given in g/L at 0 °C and 760 mm Hg (1 atm). Density of liquids is given in g/cm^3 at 20 °C.

(b) Because air is a mixture, it does not have a true molecular weight. This is the average molecular weight of its constituents.

(c) Subl. indicates that the substance sublimes at the temperature listed.

Table 7 Approximate equivalent hardness numbers for nonaustenitic steels (Rockwell C hardness range)

For carbon and alloy steels in the annealed, normalized, and quenched-and-tempered conditions.

Rockwell C hardness No., 150 kgf, HRC	Vickers hardness No., HV	Brinell hardness No.		Knoop hardness No., 500 gf and over, HK	Rockwell hardness No.		Rockwell superficial hardness No.			Sclerscope hardness No.	Rockwell C Tensile strength (approximate) ksi
		10 mm standard ball, 3000 kgf, HBS	10 mm carbide ball, 3000 kgf, HBW		A scale, 60 kgf, HRA	D scale, 100 kgf, HRD	15-N scale, 15 kgf, HR-15-N	30-N scale, 30 kgf, HR 30-N	45-N scale, 45 kgf, HR 45-N		
68	940	. . .	. . .	920	85.6	76.9	93.2	894.4	75.4	97.3	. . .
67	900	. . .	. . .	895	85.0	76.1	92.9	83.6	74.2	95.0	. . .
66	865	. . .	. . .	870	84.5	75.4	92.5	82.8	73.3	92.7	. . .
65	832	. . .	(739)	846	83.9	74.5	92.2	81.9	72.0	90.6	. . .
64	800	. . .	(722)	822	83.4	73.8	91.8	81.1	71.0	88.5	. . .
63	772	. . .	(705)	799	82.8	73.0	91.4	80.1	69.9	86.5	. . .
62	746	. . .	(688)	776	82.3	72.2	91.1	79.3	68.8	84.5	. . .
61	720	. . .	(670)	754	81.8	71.5	90.7	78.4	67.7	82.6	. . .
60	697	. . .	(654)	732	81.2	70.7	90.2	77.5	66.6	80.8	. . .
59	674	. . .	(634)	710	80.7	69.9	89.8	76.6	65.5	79.0	351
58	653	. . .	615	690	80.1	69.2	89.3	75.7	64.3	77.3	338
57	633	. . .	595	670	79.6	68.5	88.9	74.8	63.2	75.6	325
56	613	. . .	577	650	79.0	67.7	88.3	73.9	62.0	74.0	313
55	595	. . .	560	630	68.5	66.9	87.9	73.0	60.9	72.4	301
54	577	. . .	543	612	78.0	66.1	87.4	72.0	59.8	70.9	292
53	560	. . .	525	594	77.4	65.4	86.9	71.2	58.6	69.4	283

52	544	(500)	512	576	76.8	64.6	86.4	70.2	57.4	67.9	273
51	528	(487)	496	558	76.3	63.8	85.9	69.4	56.1	66.5	264
50	513	(475)	481	542	75.9	63.1	85.5	68.5	55.0	65.1	255
49	498	(464)	469	526	75.2	62.1	85.0	67.6	53.8	63.7	246
48	484	451	455	510	74.7	61.4	84.5	66.7	52.5	62.4	238
47	471	442	443	495	74.1	60.8	83.9	65.8	51.4	61.1	229
46	458	432	432	480	73.6	60.0	83.5	64.8	50.3	59.8	221
45	446	421	421	466	73.1	59.2	83.0	64.0	49.0	58.5	215
44	434	409	409	452	72.5	58.5	82.5	63.1	47.8	57.3	208
43	423	400	400	438	72.0	57.7	82.0	62.2	46.7	56.1	201
42	412	390	390	426	71.5	56.9	81.5	61.3	45.5	54.9	194
41	402	381	381	414	70.9	56.2	80.9	60.4	44.3	53.7	188
40	392	371	371	402	70.4	55.4	80.4	59.5	43.1	52.6	182
39	382	362	362	391	69.9	54.6	79.9	58.6	41.9	51.5	177
38	372	353	353	380	69.4	53.8	79.4	57.7	40.8	50.4	171
37	363	344	344	370	68.9	53.1	78.8	56.8	39.6	49.3	166
36	354	336	336	360	68.4	52.3	78.3	55.9	38.4	48.2	161
35	345	327	327	351	67.9	51.5	77.7	55.0	37.2	47.1	156
34	336	319	319	342	67.4	50.8	77.2	54.2	36.1	46.1	152
33	327	311	311	334	66.8	50.0	76.6	53.3	34.9	45.1	149
32	318	301	301	326	66.3	49.2	76.1	52.1	33.7	44.1	146

31	310	294	294	318	65.8	48.4	75.6	51.3	32.5	43.1	141
30	302	286	286	311	65.3	47.7	75.0	50.4	31.3	42.2	138
29	294	279	279	304	64.8	47.0	74.5	49.5	30.1	41.3	135
28	286	271	271	297	64.3	46.1	73.9	48.6	28.9	40.4	131
27	279	264	264	290	63.8	45.2	73.3	47.7	27.8	39.5	128
26	272	258	258	284	63.3	44.6	72.8	46.8	26.7	38.7	125
25	266	253	253	278	62.3	43.8	72.2	45.9	25.5	37.8	123
24	260	247	247	272	62.4	43.1	71.6	45.0	24.3	37.0	119
23	254	243	243	266	62.0	42.1	71.0	44.0	23.1	36.3	117
22	248	237	237	261	61.5	41.6	70.5	43.2	22.0	35.5	115
21	243	231	231	256	61.0	40.9	69.9	42.3	20.7	34.8	112
20	238	226	226	251	60.5	40.1	69.4	41.5	19.6	34.2	110

Note: Values in parenthesis are beyond the normal range and are presented for information only. Source: ASTM E 140

Table 8 Approximate equivalent hardness numbers for nonaustenitic steels (rockwell B hardness range)

For carbon and alloy steels in the annealed, normalized, and quenched-and-tempered conditions

Rockwell B hardness No., 100 kgf, HRB	**Vickers hardness No., HV**	**Brinell hardness No., 3000 kgf, HBS**	**Knoop hardness No., 500 gf and over, HK**	**Rockwell A hardness No., 60 kgf, HRA**	**Rockwell F hardness No., 60 kgf, HRF**	**Rockwell superficial hardness No.**			**Tensile strength (approximate), ksi**	**Rockwell B hardness No., 100 kgf, HRB**
						15-T scale, 15 kgf, HR 15-T	**30-T scale, 30 kgf, HR 30-T**	**45-T scale, 45 kgf, HR 45-T**		
100	240	240	251	61.5	. . .	93.1	83.1	72.9	116	100
99	234	234	246	60.9	. . .	92.8	82.5	71.9	114	99
98	228	228	241	60.2	. . .	92.5	81.8	70.9	109	98

97	222	222	236	59.5	. . .	92.1	81.1	69.9	104	97
96	216	216	231	58.9	. . .	91.8	80.4	68.9	102	96
95	210	210	226	58.3	. . .	91.5	79.8	67.9	100	95
49	205	205	221	57.6	. . .	91.2	79.1	66.9	98	94
93	200	200	216	57.0	. . .	90.8	78.4	65.9	94	93
92	195	195	211	56.4	. . .	90.5	77.8	64.8	92	92
91	190	190	206	55.8	. . .	90.2	77.1	63.8	90	91
90	185	185	201	55.2	. . .	89.9	76.4	62.8	89	90
89	180	180	196	54.6	. . .	89.5	75.8	61.8	88	89
88	176	176	192	54.0	. . .	89.2	75.1	60.8	86	88
87	172	172	188	53.4	. . .	88.9	74.4	59.8	84	87
86	169	169	184	52.8	. . .	88.6	73.8	58.8	83	86
85	165	165	180	52.3	. . .	88.2	73.1	57.8	82	85
84	162	162	176	51.7	. . .	87.9	72.4	56.8	81	84
83	159	159	173	51.1	. . .	87.6	71.8	55.8	80	83
82	156	156	170	50.6	. . .	87.3	71.1	54.8	77	82
81	153	153	167	50.0	. . .	86.9	70.4	53.8	73	81
80	150	150	164	49.5	. . .	86.6	69.7	52.8	72	80
79	147	147	161	48.9	. . .	86.3	69.1	51.8	70	79
78	144	144	158	48.4	. . .	86.0	68.4	50.8	69	78
77	141	141	155	47.9	. . .	85.6	67.7	49.8	68	77

76	139	139	152	47.3	. . .	85.3	67.1	48.8	67	76
75	137	137	150	46.8	99.6	85.0	66.4	47.8	66	75
74	135	135	147	46.3	99.1	84.7	65.7	46.8	65	74
73	132	132	145	45.8	98.5	84.3	65.1	45.8	64	73
72	130	130	143	45.3	98.0	84.0	64.4	44.8	63	72
71	127	127	141	44.8	97.4	83.7	63.7	43.8	62	71
70	125	125	139	44.3	96.8	83.4	63.1	42.8	61	70
69	123	123	137	43.8	96.2	83.0	62.4	41.8	60	69
68	121	121	135	43.3	95.6	82.7	61.7	40.8	59	68
67	119	119	133	42.8	95.1	82.4	61.0	39.8	58	67
66	117	117	131	42.3	94.5	82.1	60.4	38.7	57	66
65	116	116	129	41.8	93.9	81.8	59.7	37.7	56	65
64	114	114	127	41.4	93.4	81.4	59.0	36.7	. . .	64
63	112	112	125	40.9	92.8	81.1	58.4	35.7	. . .	63
62	110	110	124	40.4	92.2	80.8	57.7	34.7	. . .	62
61	108	108	122	40.0	91.7	80.5	57.0	33.7	. . .	61
60	107	107	120	39.5	91.1	80.1	56.4	32.7	. . .	60
59	106	106	118	39.0	90.5	79.8	55.7	31.7	. . .	59
58	104	104	117	38.6	90.0	79.5	55.0	30.7	. . .	58
57	103	103	115	38.1	89.4	79.2	54.4	29.7	. . .	57
56	101	101	114	37.7	88.8	78.8	53.7	28.7	. . .	56

55	100	100	112	37.2	88.2	78.5	50.0	27.7	. . .	55
54	. . .	. . .	111	36.8	87.7	78.2	52.4	26.7	. . .	54
53	. . .	. . .	110	36.3	87.1	77.9	51.7	25.7	. . .	53
52	. . .	. . .	109	35.9	86.5	77.5	51.0	24.7	. . .	52
51	. . .	. . .	108	35.5	86.0	77.2	50.3	23.7	. . .	51
50	. . .	. . .	107	35.0	85.4	76.9	49.7	22.7	. . .	50
49	. . .	. . .	106	34.6	84.8	76.6	49.0	21.7	. . .	49
48	. . .	. . .	105	34.1	84.3	76.2	48.3	20.7	. . .	48
47	. . .	. . .	104	33.7	83.7	75.9	47.7	19.7	. . .	47
46	. . .	. . .	103	33.3	83.1	75.6	47.0	18.7	. . .	46
45	. . .	. . .	102	32.9	82.6	75.3	46.3	17.7	. . .	45
44	. . .	. . .	101	32.4	82.0	74.9	45.7	16.7	. . .	44
43	. . .	. . .	100	32.0	81.4	74.6	45.0	15.7	. . .	43
42	. . .	. . .	99	31.6	80.8	74.3	44.3	14.7	. . .	42
41	. . .	. . .	98	31.2	80.3	74.0	43.7	13.6	. . .	41
40	. . .	. . .	97	30.7	79.7	73.6	43.0	12.6	. . .	40
39	. . .	. . .	96	30.3	79.1	73.3	42.3	11.6	. . .	39
38	. . .	. . .	95	29.9	78.6	73.0	41.0	10.6	. . .	38
37	. . .	. . .	94	29.5	78.0	72.7	41.0	9.6	. . .	37
36	. . .	. . .	93	29.1	77.4	72.3	40.3	8.6	. . .	36
35	. . .	. . .	92	28.7	76.9	72.0	39.6	7.6	. . .	35

34	. . .	. . .	91	28.2	76.3	71.7	39.0	6.6	. . .	34
33	. . .	. . .	90	27.8	75.7	71.4	38.3	5.6	. . .	33
32	. . .	. . .	89	27.4	75.2	71.0	37.6	4.6	. . .	32
31	. . .	. . .	88	27.0	74.6	70.7	37.0	3.6	. . .	31
30	. . .	. . .	87	26.6	74.0	70.4	36.3	2.6	. . .	30

Source: ASTM E 140

Table 9 Approximate equivalent hardness numbers for austenitic stainless steel sheet (Rockwell C hardness range)

For types 201, 202, 301, 302, 304, 304L, 305, 316, 316L, 321 and 347. Tempers range from annealed to extra hard for type 301, with a smaller range for the other types. Test coupon thickness; 0.1 to 0.050 in. (2.5 to 1.27 mm)

Rockwell hardness No.		**Rockwell superficial hardness No.**		
C scale, 150 kgf, diamond penetrator, HRC	**A scale, 60 kgf, diamond penetrator, HRA**	**15-N scale, 15 kgf, superficial diamond penetrator, HR 15-N**	**30-N scale, 30 kgf, superficial diamond penetrator, HR 30-N**	**45-N scale, 45 kgf, superficial diamond penetrator, HR 45-N**
48	74.4	84.1	66.2	52.1
47	73.9	83.6	65.3	50.9
46	73.4	83.1	64.5	49.8
45	72.9	82.6	63.6	48.7
44	72.4	82.1	62.7	47.5
43	71.9	81.6	61.8	46.4
42	71.4	81.0	61.0	45.2
41	70.9	80.5	60.1	44.1
40	70.4	80.0	59.2	43.0
39	69.9	79.5	58.4	41.8

38	69.3	79.0	57.5	40.7
37	68.8	78.5	56.6	39.6
36	68.3	78.0	55.7	38.4
35	67.8	77.5	54.9	37.3
34	67.3	77.0	54.0	36.1
33	66.8	76.5	53.1	35.0
32	66.3	75.9	52.3	33.9
31	65.8	75.4	51.4	32.7
30	65.3	74.9	50.5	31.6
29	64.8	74.4	49.6	30.4
28	64.3	73.9	48.8	29.3
27	63.8	73.4	47.9	28.2
26	63.3	72.9	47.0	27.0
25	62.8	72.4	40.2	25.9
24	62.3	71.9	45.3	24.8
23	61.8	71.3	44.4	23.6
22	61.3	70.8	43.5	22.5
21	60.8	70.3	42.7	21.3

Source: ASTM E 140

Table 10 Approximate equivalent hardness numbers for austenitic stainless steel sheet (Rockwell B hardness range)

For types 201, 202, 301, 302, 304, 304L, 305, 316, 316L, 321 and 347. Tempers range from annealed to extra hard for type 301, with a smaller range for the other types. Test coupon thickness; 0.1 to 0.050 in. (2.5 to 1.27 mm)

Rockwell hardness No.			**Rockwell superficial hardness No.**		
B scale, 100 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HRB	**A scale, 60 kgf, diamond penetrator, HRA**	**F scale, 60 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HRF**	**15-T scale, 15 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 15-T**	**30-T scale, 30 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 30-T**	**45-T scale, 45 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 45-T**
100	61.5	(113.9)	91.5	80.4	70.2
99	60.9	(113.2)	91.2	79.7	69.2
98	60.3	(112.5)	90.8	79.0	68.2
97	59.7	(111.8)	90.4	78.3	67.2
96	59.1	(111.1)	90.1	77.7	66.1
95	58.5	(110.5)	89.7	77.0	65.1
94	58.0	(109.8)	89.3	76.3	64.1
93	57.4	(109.1)	88.9	75.6	63.1
92	56.8	(108.4)	88.6	74.9	62.1
91	56.2	(107.8)	88.2	74.2	61.1
90	55.6	(107.1)	87.8	73.5	60.1
89	55.0	(106.4)	87.5	72.8	59.0
88	54.5	(105.7)	87.1	72.1	58.0
87	53.9	(105.0)	86.7	71.4	57.0
86	53.3	(104.4)	86.4	70.7	56.0
85	52.7	(103.7)	86.0	70.0	55.0

84	52.1	(103.0)	85.6	69.3	54.0
83	51.5	(102.3)	85.2	68.6	52.9
82	50.9	(101.7)	84.9	67.9	51.9
81	50.4	(101.0)	84.5	67.2	50.9
80	49.8	(100.3)	84.1	66.5	49.9
79	49.2	99.6	83.8	65.8	48.9
78	48.6	99.0	83.4	65.1	47.9
77	48.0	98.3	83.0	64.4	46.8
76	47.4	97.6	82.6	63.7	45.8
75	46.9	96.9	82.3	63.0	44.8
74	46.3	96.2	81.9	62.4	43.8
73	45.7	95.6	81.5	61.7	42.8
72	45.1	94.9	81.2	61.0	41.8
71	44.5	94.2	80.8	60.3	40.7
70	43.9	93.5	80.4	59.6	39.7
69	43.3	92.8	80.1	58.9	38.7
68	42.8	92.2	79.7	58.2	37.7
67	42.2	91.5	79.3	57.5	36.7
66	41.6	90.8	78.9	56.8	35.7
65	41.0	90.1	78.6	56.1	34.7
64	40.4	89.5	78.2	55.4	33.6

63	39.8	88.8	77.8	54.7	32.6
62	39.3	88.1	77.5	54.0	31.6
61	38.7	87.4	77.1	53.3	30.6
60	38.1	86.8	76.7	52.6	29.6

Note: Rockwell F numbers in parenthesis are beyond the normal range and are presented for information only. Source: ASTM E 140

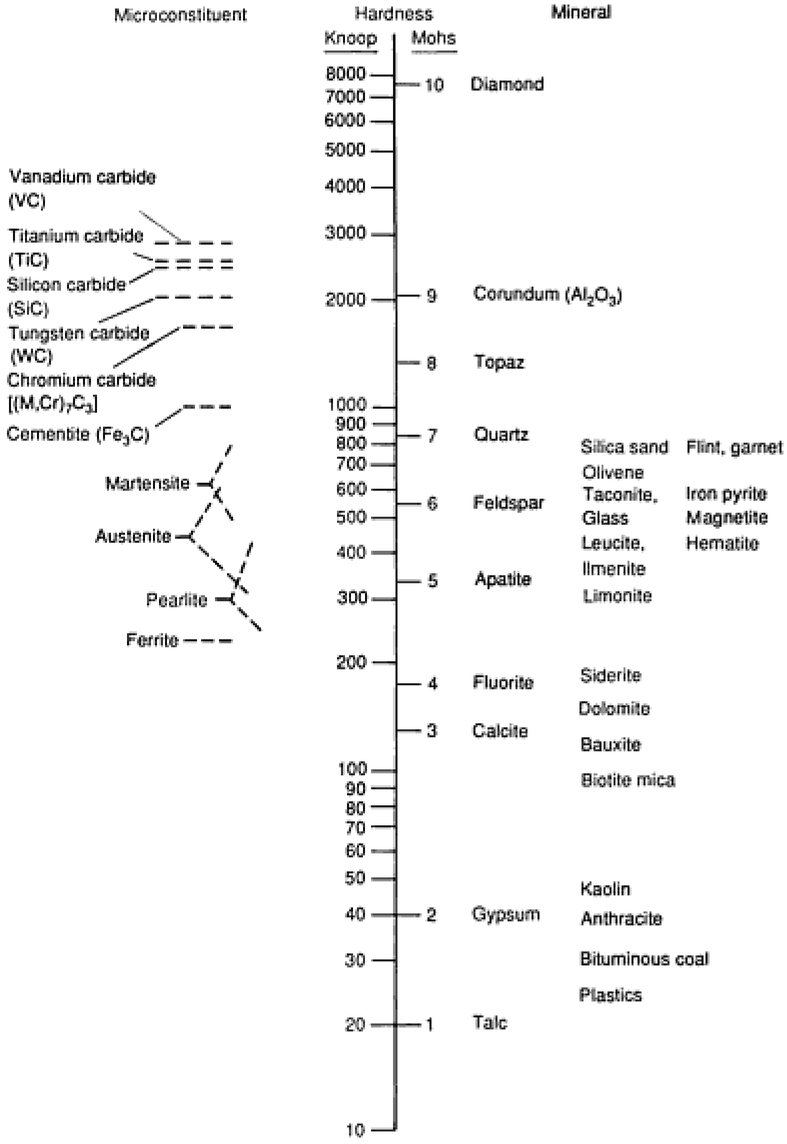

Microconstituent
Hardness
Knoop
Mohs
Mineral
8000
7000
6000
5000
4000
3000
2000
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10
10 Diamond
9 Corundum (Al2O3)
8 Topaz
7 Quartz
6 Feldspar
5 Apatite
4 Fluorite
3 Calcite
2 Gypsum
1 Talc
Vanadium carbide (VC)
Titanium carbide (TiC)
Silicon carbide (SiC)
Tungsten carbide (WC)
Chromium carbide [(M,Cr)7C3]
Cementite (Fe3C)
Martensite
Austenite
Pearlite
Ferrite
Silica sand
Flint, garnet
Olivene
Taconite,
Iron pyrite
Glass
Magnetite
Leucite,
Hematite
Ilmenite
Limonite
Siderite
Dolomite
Bauxite
Biotite mica
Kaolin
Anthracite
Bituminous coal
Plastics

Fig. 1 Hardness of some alloy microconstituents and minerals

Table 11 Approximate Brinell-Rockwell B hardness numbers for equivalent austenitic stainless steel plate in the annealed condition

Rockwell hardness No., B scale (100 kgf, 1.588 mm ball) HRB	**Brinell hardness No. (3000 kgf, 10 mm steel ball), HBS**
100	256
99	248
98	240
97	233
96	226
95	219
94	213
93	207
92	202
91	197
90	192
89	187
88	183
87	178
86	174
85	170
84	167
83	163

82	160
81	156
80	153
79	150
78	147
77	144
76	142
75	139
74	137
73	135
72	132
71	130
70	128
69	126
68	124
67	122
66	120
65	118
64	116
63	114
62	113

61	111
60	110

Table 12 Approximate equivalent hardness numbers for wrought aluminum products

Brinell hardness No., 500 kgf, 10 mm ball, HBS	**Vickers hardness No., 15 kgf, HV**	**Rockwell hardness No.**			**Rockwell superficial hardness No.**		
		B scale, 100 kgf, $\frac{1}{16}$ in. ball, HRB	**E scale, 100 kgf, $\frac{1}{8}$ in. ball, HRE**	**H scale, 60 kgf, $\frac{1}{8}$ in. ball, HRH**	**15-T scale, 15 kgf, $\frac{1}{16}$ in. ball, HR 15-T**	**30-T scale, 30 kgf, $\frac{1}{16}$ in. ball, HR 30-T**	**15-W scale, 15 kgf, $\frac{1}{8}$ in. ball, HR 15-W**
160	189	91	. . .	. . .	89	77	95
155	183	90	. . .	. . .	89	76	95
150	177	89	. . .	. . .	89	75	94
145	171	87	. . .	. . .	88	74	94
140	165	86	. . .	. . .	88	73	94
135	159	84	. . .	. . .	87	71	93
130	153	81	. . .	. . .	87	70	93
125	147	79	. . .	. . .	86	68	92
120	141	76	101	. . .	86	67	92
115	135	72	100	. . .	86	65	91
110	129	69	99	. . .	85	63	91
105	123	65	98	. . .	84	61	91
100	117	60	. . .	. . .	83	59	90
95	111	56	96	. . .	82	57	90
90	105	51	94	108	81	54	89

85	98	46	91	107	80	52	89
80	92	40	88	106	78	50	88
75	86	34	84	104	76	47	87
70	80	28	80	102	74	44	86
65	74	. . .	75	100	72	. . .	85
60	68	. . .	70	97	70	. . .	83
55	62	. . .	65	94	67	. . .	82
50	56	. . .	59	91	64	. . .	80
45	50	. . .	53	87	62	. . .	79
40	44	. . .	46	83	59	. . .	77

Source: ASTM E 140

Table 13 Approximate equivalent hardness numbers for wrought coppers (>99% Cu, alloys C10200 through C14200)

Vickers hardness No.		**Knoop hardness No.**		**Rockwell superficial hardness No.**			**Rockwell hardness No.**		**Rockwell superficial hardness No.**			**Brinell hardness No.**	
				15-T scale, 15 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 15-T 0.010 in. (0.25 mm) strip	**15-T scale, 15 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 15-T**	**30-T scale, 30 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 30-T**	**No. B scale, 100 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HRB**	**No. F scale, 60 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HRF**	**15-T scale, 15 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 15-T**	**30-T scale, 30 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 30-T**	**45-T scale, 45 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 45-T**	**500 kgf, 10 mm diameter ball, HBS, 0.080 in. (2.03 mm) strip**	**20 kgf, 2 mm diameter ball, HBS, 0.040 in (1.02 mm) strip**
1 kgf HV	**100 gf HV**	**1 kgf, HK**	**500 gf, HK**		**0.020 in. (0.51 mm) strip**		**0.040 in. (1.02 mm) strip and greater**						
130	127.0	138.7	133.8	. . .	85.0	. . .	67.0	99.0	. . .	69.5	49.0	. . .	119.0
128	125.2	136.8	132.1	83.0	84.5	. . .	66.0	98.0	87.0	68.5	48.0	. . .	117.5
126	123.6	134.9	130.4	. . .	84.0	. . .	65.0	97.0	. . .	67.5	46.5	120.0	115.0

124	121.9	133.0	128.7	82.5	83.5	. . .	64.0	96.0	86.0	66.5	45.0	117.5	113.0
122	121.1	131.0	127.0	. . .	83.0	. . .	62.5	95.5	85.5	66.0	44.0	115.0	111.0
120	118.5	129.0	125.2	82.0	82.5	. . .	61.0	95.0	. . .	65.0	42.5	112.0	109.0
118	116.8	127.1	123.5	81.5	. . .	. . .	59.5	94.0	85.0	64.0	41.0	110.0	107.5
116	115.0	125.1	121.7	. . .	82.0	. . .	58.5	93.0	. . .	63.0	40.0	107.0	105.5
114	113.5	123.2	119.9	81.0	81.5	. . .	57.0	92.5	84.5	62.0	38.5	105.0	103.5
112	111.8	121.4	118.1	80.5	81.0	. . .	55.0	91.5	. . .	61.0	37.0	102.0	102.0
110	109.9	119.5	116.3	80.0	. . .	. . .	53.5	91.0	84.0	60.0	36.0	99.5	100.0
108	108.3	117.5	114.5	. . .	80.5	. . .	52.0	90.5	83.5	59.0	34.5	97.0	98.0
106	106.6	115.6	112.6	79.5	80.0	. . .	50.0	89.5	. . .	58.0	33.0	94.5	96.0
104	104.9	113.5	110.1	79.0	79.5	. . .	48.0	88.5	83.0	57.0	32.0	92.0	94.0
102	103.2	111.5	108.0	78.5	79.0	. . .	46.5	87.5	82.5	56.0	30.0	89.5	92.0
100	101.5	109.4	106.0	78.0	78.0	. . .	44.5	87.0	82.0	55.0	28.5	87.0	90.0
98	99.8	107.3	104.0	77.5	77.5	. . .	42.0	85.5	81.0	53.5	26.5	84.5	88.0
96	98.0	105.3	102.1	77.0	77.0	. . .	40.0	84.5	80.5	52.0	25.5	82.0	86.5
94	96.4	103.2	100.0	76.5	76.5	. . .	38.0	83.0	80.0	51.0	23.0	79.5	85.0
92	94.7	101.0	98.0	76.0	75.5	. . .	35.5	82.0	79.0	49.0	21.0	77.0	83.0
90	93.0	98.9	96.0	75.5	75.0	. . .	33.0	81.0	78.0	47.5	19.0	74.5	81.0
88	91.2	96.9	94.0	75.0	74.5	. . .	30.5	79.5	77.0	46.0	16.5	. . .	79.0
86	89.7	95.5	92.0	74.5	73.5	. . .	28.0	78.0	76.0	44.0	14.0	. . .	77.0
84	87.9	92.3	90.0	74.0	73.0	. . .	25.5	76.5	75.0	43.0	12.0	. . .	75.0

82	86.1	90.1	87.9	73.5	72.0	. . .	23.0	74.5	74.5	41.0	9.5	. . .	73.0
80	84.5	87.9	86.0	72.5	71.0	. . .	20.0	73.0	73.5	39.5	7.0	. . .	71.5
78	82.8	85.7	84.0	72.0	70.0	. . .	17.0	71.0	72.5	37.5	5.0	. . .	69.5
76	81.0	83.5	81.9	71.5	69.5	. . .	14.5	69.0	71.5	36.0	2.0	. . .	67.5
74	79.2	81.1	79.9	71.0	68.5	. . .	11.5	67.5	70.0	34.0	. . .	. . .	66.0
72	77.6	78.9	78.7	70.0	67.5	. . .	8.5	66.0	69.0	32.0	. . .	. . .	64.0
70	75.8	76.8	76.6	69.5	66.5	. . .	5.0	64.0	67.5	30.0	. . .	. . .	62.0
68	74.3	74.1	74.4	69.0	65.5	. . .	2.0	62.0	66.0	28.0	. . .	. . .	60.5
66	72.6	71.9	71.9	68.0	64.5	. . .	. . .	60.0	64.5	25.5	. . .	. . .	58.5
64	70.9	69.5	70.0	67.5	63.5	. . .	. . .	58.0	63.5	23.5	. . .	. . .	57.0
62	69.1	67.0	67.9	66.5	62.0	. . .	. . .	56.0	61.0	21.0	. . .	. . .	55.0
60	67.5	64.6	65.9	66.0	61.0	. . .	. . .	54.0	59.0	18.0	. . .	. . .	53.0
58	65.8	62.0	63.8	65.0	60.0	. . .	. . .	51.5	57.0	15.5	. . .	. . .	51.5
56	64.0	59.8	61.8	64.5	58.5	. . .	. . .	49.0	55.0	13.0	. . .	. . .	49.5
54	62.3	57.4	59.5	63.5	57.5	. . .	. . .	47.0	53.0	10.0	. . .	. . .	48.0
52	60.7	55.0	57.2	63.0	56.0	. . .	. . .	44.0	51.5	7.5	. . .	. . .	46.5
48	57.3	50.3	52.7	61.0	53.5	. . .	. . .	39.0	47.5	1.5	. . .	. . .	42.0
46	55.8	48.0	50.2	60.5	52.0	. . .	. . .	36.0	45.0	. . .	. . .	. . .	41.0
44	53.9	45.9	47.8	59.5	51.0	. . .	. . .	33.5	43.0	. . .	. . .	. . .	. . .
42	52.2	43.7	45.2	58.5	49.5	. . .	. . .	30.5	41.0	. . .	. . .	. . .	. . .
40	51.3	40.2	42.8	57.5	48.0	. . .	. . .	28.0	38.5	. . .	. . .	. . .	. . .

Source: ASTM E 140

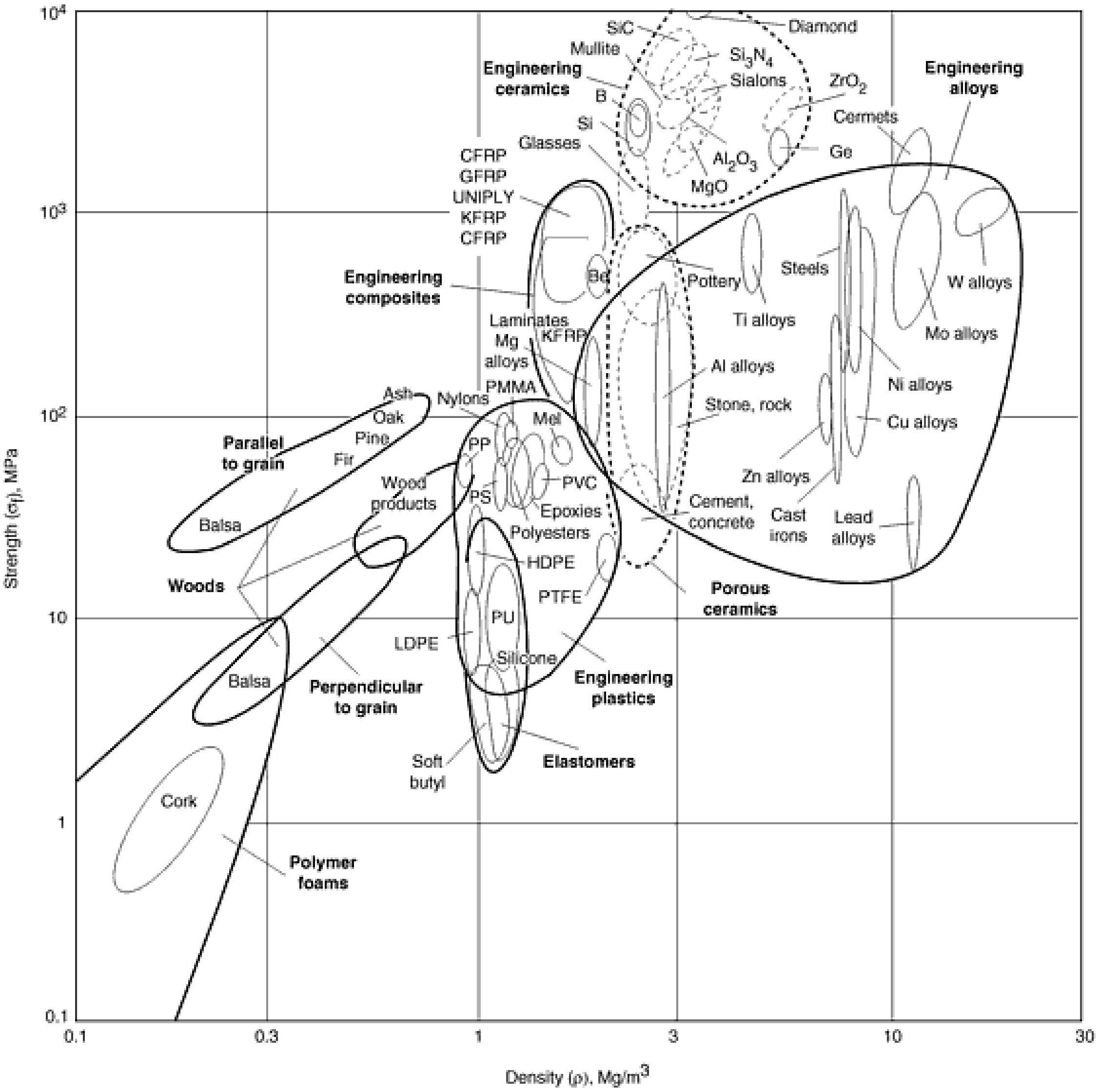


Fig. 2 Strength versus density for various engineered materials. Strength is yield strength for metals/alloys and polymers, compressive strength for ceramics (note the broken property envelope lines), tear strength for elastomers, and tensile strength for composites. It should be noted that the tensile strength of engineering ceramics is about 15 times smaller than its compressive strength. Abbreviation key: CFRP, carbon-fiber reinforced polymer; GFRP, glass-fiber reinforced polymer; KFRP, kevlar-fiber reinforced polymer; PMMA, polymethyl methacrylate; Mel, melamines; PP, polypropylene; PC, polycarbonate; PS, polystyrene; PVC, polyvinyl chloride; HDPE, high-density polyethylene; LDPE, low-density polyethylene; PTFE, polytetrafluoroethylene; PU, polyurethane

Table 14 Approximate equivalent hardness numbers for cartridge brass (70% Cu, 30% Zn)

Vickers hardness No., HV	Rockwell hardness No.		Rockwell superficial hardness No.			Brinell hardness No., 500 kgf, 10 mm ball, HBS
	B scale, 100 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HRB	F scale, 60 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HRF	15-T scale, 15 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 15-T	30-T scale, 30 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 30-T	45-T scale, 45 kgf, $\frac{1}{16}$ in. (1.588 mm) ball, HR 45-T	
196	93.5	110.0	90.0	77.5	66.0	169
194	. . .	109.5	. . .	. . .	65.5	167
192	93.0	. . .	. . .	77.0	65.0	166
190	92.5	109.0	. . .	76.5	64.5	164
188	92.0	. . .	89.5	. . .	64.0	162
186	91.5	108.5	. . .	76.0	63.5	161
184	91.0	. . .	. . .	75.5	63.0	159
182	90.5	108.0	89.0	. . .	62.5	157
180	90.0	107.5	. . .	75.0	62.0	156
178	89.0	. . .	. . .	74.5	61.5	154
176	88.5	107.0	. . .	. . .	61.0	152
174	88.0	. . .	88.5	74.0	60.5	150
172	87.5	106.5	. . .	73.5	60.0	149
170	87.0	. . .	. . .	. . .	59.5	147
168	86.0	106.0	88.0	73.0	59.0	146
166	85.5	. . .	. . .	72.5	58.5	144

164	85.0	105.5	. . .	72.0	58.0	142
162	84.0	105.0	87.5	. . .	57.5	141
160	83.5	. . .	. . .	71.5	56.5	139
158	83.0	104.5	. . .	71.0	56.0	138
156	82.0	104.0	87.0	70.5	55.5	136
154	81.5	103.5	. . .	70.0	54.5	135
152	80.5	103.0	. . .	. . .	54.0	133
150	80.0	. . .	86.5	69.5	53.5	131
148	79.0	102.5	. . .	69.0	53.0	129
146	78.0	102.0	. . .	68.5	52.5	128
144	77.5	101.5	86.0	68.0	51.5	126
142	77.0	101.0	. . .	67.5	51.0	124
140	76.0	100.5	85.5	67.0	50.0	122
138	75.0	100.0	. . .	66.5	49.0	121
136	74.5	99.5	85.0	66.0	48.0	120
134	73.5	99.0	. . .	65.5	47.5	118
132	73.0	98.5	84.5	65.0	46.5	116
130	72.0	98.0	84.0	64.5	45.5	114
128	71.0	97.5	. . .	63.5	45.0	113
126	70.0	97.0	83.5	63.0	44.0	112
124	69.0	96.5	. . .	62.5	43.0	110

122	68.0	96.0	83.0	62.0	42.0	108
120	67.0	95.5	. . .	61.0	41.0	106
118	66.0	95.0	82.5	60.5	40.0	105
116	65.0	94.5	82.0	60.0	39.0	103
114	64.0	94.0	81.5	59.5	38.0	101
112	63.0	93.0	81.0	58.5	37.0	99
110	62.0	92.6	80.5	58.0	35.5	97
108	61.0	92.0	. . .	57.0	34.5	95
106	59.5	91.2	80.0	56.0	33.0	94
104	58.0	90.5	79.5	55.0	32.0	92
102	57.0	89.8	79.0	54.5	30.5	90
100	56.0	89.0	78.5	53.5	29.5	88
98	54.0	88.0	78.0	52.5	28.0	86
96	53.0	87.2	77.5	51.5	26.5	85
94	51.0	86.3	77.0	50.5	24.5	83
92	49.5	85.4	76.5	49.0	23.0	82
90	47.5	84.4	75.5	48.0	21.0	80
88	46.0	83.5	75.0	47.0	19.0	79
86	44.0	82.3	74.5	45.5	17.0	77
84	42.0	81.2	73.5	44.0	14.5	76
82	40.0	80.0	73.0	43.0	12.5	74

80	37.5	78.6	72.0	41.0	10.0	72
78	35.0	77.4	71.5	39.5	7.5	70
76	32.5	76.0	70.5	38.0	4.5	68
74	30.0	74.8	70.0	36.0	1.0	66
72	27.5	73.2	69.0	34.0	. . .	64
70	24.5	71.8	68.0	32.0	. . .	63
68	21.5	70.0	67.0	30.0	. . .	62
66	18.5	68.5	66.0	28.0	. . .	61
64	15.5	66.8	65.0	25.5	. . .	59
62	12.5	65.0	63.5	23.0	. . .	57
60	10.0	62.5	62.5	. . .	. . .	55
58	. . .	61.0	61.0	18.0	. . .	53
56	. . .	58.8	60.0	15.0	. . .	52
54	. . .	56.5	58.5	12.0	. . .	50
52	. . .	53.5	57.0	. . .	. . .	48
50	. . .	50.5	55.5	. . .	. . .	47
49	. . .	49.0	54.5	. . .	. . .	46
48	. . .	47.0	53.5	. . .	. . .	45
47	. . .	45.0	. . .	. . .	. . .	44
46	. . .	43.0	. . .	. . .	. . .	43
45	. . .	40.0	. . .	. . .	. . .	42

Source: ASTM E 140

Table 15 Guide to the Unified Numbering System (UNS) for metals and alloys

For additional details on the UNS, see the combined ASTM E 527/SAE J1066 standard, "Recommended Practice for Numbering Metals and Alloys."

UNS series	Metal/alloy
Nonferrous metals and alloys	
A00001-A99999	Aluminum and aluminum alloys
C00001-C99999	Copper and copper alloys
E00001-E99999	Rare earth and rare earth-like metals and alloys
E00001-E00999	Actinium
E01000-E20999	Cerium
E21000-E45999	Mixed rare earths (e.g., mischmetal)
E46000-E47999	Dysprosium
E48000-E49999	Erbium
E50000-E51999	Europium
E52000-E55999	Gadolinium
E56000-E57999	Holmium
E58000-E67999	Lanthanum
E68000-E68999	Lutetium
E69000-E73999	Neodymium
E74000-E77999	Praseodymium
E78000-E78999	Promethium

E79000-E82999	Samarium
E83000-E84999	Scandium
E85000-E86999	Terbium
E87000-E87999	Thulium
E88000-E89999	Ytterbium
E90000-E99999	Yttrium
L00001-L99999	Low-melting-point metals and alloys
L00001-L00999	Bismuth
L01001-L01999	Cadmium
L02001-L02999	Cesium
L03001-L03999	Gallium
L04001-L04999	Indium
L06001-L06999	Lithium
L07001-L07999	Mercury
L08001-L08999	Potassium
L09001-L09999	Rubidium
L10001-L10999	Selenium
L11001-L11999	Sodium
L13001-L13999	Tin
L50001-L59999	Lead

M00001-M99999	Miscellaneous nonferrous metals and alloys
M00001-M00999	Antimony
M01001-M01999	Arsenic
M02001-M02999	Barium
M03001-M03999	Calcium
M04001-M04999	Germanium
M05001-M05999	Plutonium
M06001-M06999	Strontium
M07001-M07999	Tellurium
M08001-M08999	Uranium
M10001-M19999	Magnesium
M20001-M29999	Manganese
M30001-M39999	Silicon
P00001-P99999	Precious metals and alloys
P00001-P00999	Gold
P01001-P01999	Iridium
P02001-P02999	Osmium
P03001-P03999	Palladium
P04001-P04999	Platinum
P05001-P05999	Rhodium

P06001-P06999	Ruthenium
P07001-P07999	Silver
R00001-R99999	Reactive and refractory metals and alloys
R01001-R01999	Boron
R02001-R02999	Hafnium
R03001-R03999	Molybdenum
R04001-R04999	Niobium (Columbium)
R05001-R05999	Tantalum
R06001-R06999	Thorium
R07001-R07999	Tungsten
R08001-R08999	Vanadium
R10001-R19999	Beryllium
R20001-R29999	Chromium
R30001-R39999	Cobalt
R40001-R49999	Rhenium
R50001-R59999	Titanium
R60001-R69999	Zirconium
Z00001-Z99999	Zinc and zinc alloys
Ferrous metals and alloys	
D00001-D99999	Specified mechanical properties of steels

F00001-F99999	Cast irons (gray, malleable, and ductile irons)
G00001-G99999	AISI and SAE carbon and alloy steels (except tool steels)
H00001-H99999	AISI and SAE H-steels (carbon, carbon-boron, and alloy H-steels)
J00001-J99999	Cast steels (except tool steels)
K00001-K99999	Miscellaneous steels and ferrous alloys
S00001-S99999	Heat- and corrosion-resistant (stainless) steels
T00001-T99999	Tool steels
Welding filler metals	
W00001-W99999	Welding filler metals, covered and tubular electrodes, classified by weld deposit composition
W00001-W09999	Carbon steel with no significant alloying elements
W10000-W19999	Manganese-molybdenum low-alloys steels
W20000-W29999	Nickel low-alloy steels
W30000-W39999	Austenitic stainless steels
W40000-W49999	Ferritic stainless steels
W50000-W59999	Chromium low-alloy steels
W60000-W69999	Copper-base alloys
W70000-W79999	Surfacing alloys
W80000-W89999	Nickel-base alloys

Table 16 SI prefixes--names and symbols

Exponential expression	**Multiplication factor**	**Prefix**	**Symbol**
10^{24}	1,000,000,000,000,000,000,000,000	yotta	Y
10^{21}	1,000,000,000,000,000,000,000	zetta	Z
10^{18}	1,000,000,000,000,000,000	exa	E
10^{15}	1,000,000,000,000,000	peta	P
10^{12}	1,000,000,000,000	tera	T
10^{9}	1,000,000,000	glga	G
10^{6}	1,000,000	meta	M
10^{3}	1,000	kilo	k
10^{2}	100	hecto(a)	h
10^{1}	10	deka(a)	da
10^{0}	1	BASE UNIT	
10^{-1}	0.1	deci(a)	d
10^{-2}	0.01	centi(a)	c
10^{-3}	0.001	milli	m
10^{-6}	0.000,001	micro	μ
10^{-9}	0.000,000,001	nano	n
10^{-12}	0.000,000,000,001	pico	p
10^{-15}	0.000,000,000,000,001	femto	f
10^{-18}	0.000,000,000,000,000,001	atto	a

10^{-21}	0.000,000,000,000,000,000,001	zepto	z
10^{-24}	0.000,000,000,000,000,000,000,001	yocto	y

(a) Nonpreferred. Prefixes should be selected in steps of 10^3 so that the resultant number before the prefix is between 0.1 and 1000. These prefixes should not be used for units of linear measurement, but may be used for higher order units. For example, the linear measurement, decimeter, is nonpreferred, but square decimeter is acceptable.

Table 17 Base, supplementary, and derived SI units

Measure	Unit	Symbol	Formula
Base units			
Amount of substance	mole	mol	
Electric current	ampere	A	
Length	meter	m	
Luminous intensity	candela	cd	
Mass	kilogram	kg	
Thermodynamic temperature	kelvin	K	
Time	second	s	
Supplementary units			
Plane angle	radian	rad	
Solid angle	steradian	sr	
Derived units			
Absorbed dose	gray	Gy	J/kg
Acceleration	meter per second squared	m/s^2	
Activity (of radionuclides)	becquerel	Bq	

Angular acceleration	radian per second squared	rad/s^2	
Angular velocity	radian per second	rad/s	
Area	square meter	m^2	
Concentration (of amount of substance)	mole per cubic meter	mol/m^3	
Current density	ampere per square meter	A/m^2	
Density, mass	kilogram per cubic meter	kg/m^3	
Dose equivalent	sievert	Sv	J/kg
Electric capacitance	farad	F	C/V
Electric charge density	coulomb per cubic meter	C/m^3	
Electric conductance	siemens	S	A/V
Electric field strength	volt per meter	V/m	
Electric flux density	coulomb per square meter	C/m^2	
Electric potential, potential difference, electromotive force	volt	V	W/A
Electric resistance	ohm	Ω	V/A
Energy, work, quantity of heat	joule	J	N · m
Energy density	joule per cubic meter	J/m^3	
Entropy	joule per kelvin	J/K	
Force	newton	N	$kg \cdot m/s^2$
Frequency	hertz	Hz	1/s
Heat capacity	joule per kelvin	J/K	
Heat flux density	watt per square meter	W/m^2	

Illuminance	lux	lx	1m/m^2
Inductance	henry	H	Wb/A
Irradiance	watt per square meter	W/m^2	
Luminance	candela per square meter	cd/m^2	
Luminous flux	lumen	lm	cd · sr
Magnetic field strength	ampere per meter	A/m	
Magnetic flux	weber	Wb	V · s
Magnetic flux density	tesla	T	Wb/m^2
Molar energy	joule per mole	J/mol	
Molar entropy	joule per mole kelvin	J/mol · K	
Molar heat capacity	joule per mole kelvin	J/mol · K	
Moment of force	newton meter	N · m	
Permeability	henry per meter	H/m	
Permittivity	farad per meter	F/m	
Power, radiant flux	watt	W	J/s
Pressure, stress	pascal	Pa	N/m^2
Quantity of electricity, electric charge	coulomb	C	A · s
Radiance	watt per square meter steradian	W/m^2 · sr	
Radiant intensity	watt per steradian	W/sr	
Specific heat capacity	joule per kilogram kelvin	J/kg · K	
Specific energy	joule per kilogram	J/kg	

Specific entropy	joule per kilogram kelvin	J/kg · K	
Specific volume	cubic meter per kilogram	M^3/kg	
Surface tension	newton per meter	N/m	
Thermal conductivity	watt per meter kelvin	W/m · K	
Velocity	meter per second	m/s	
viscosity, dynamic	pascal second	Pa · s	
Viscosity, kinematic	square meter per second	m^2/s	
Volume	cubic meter	m^3	
Wavenumber	1 per meter	1/m	

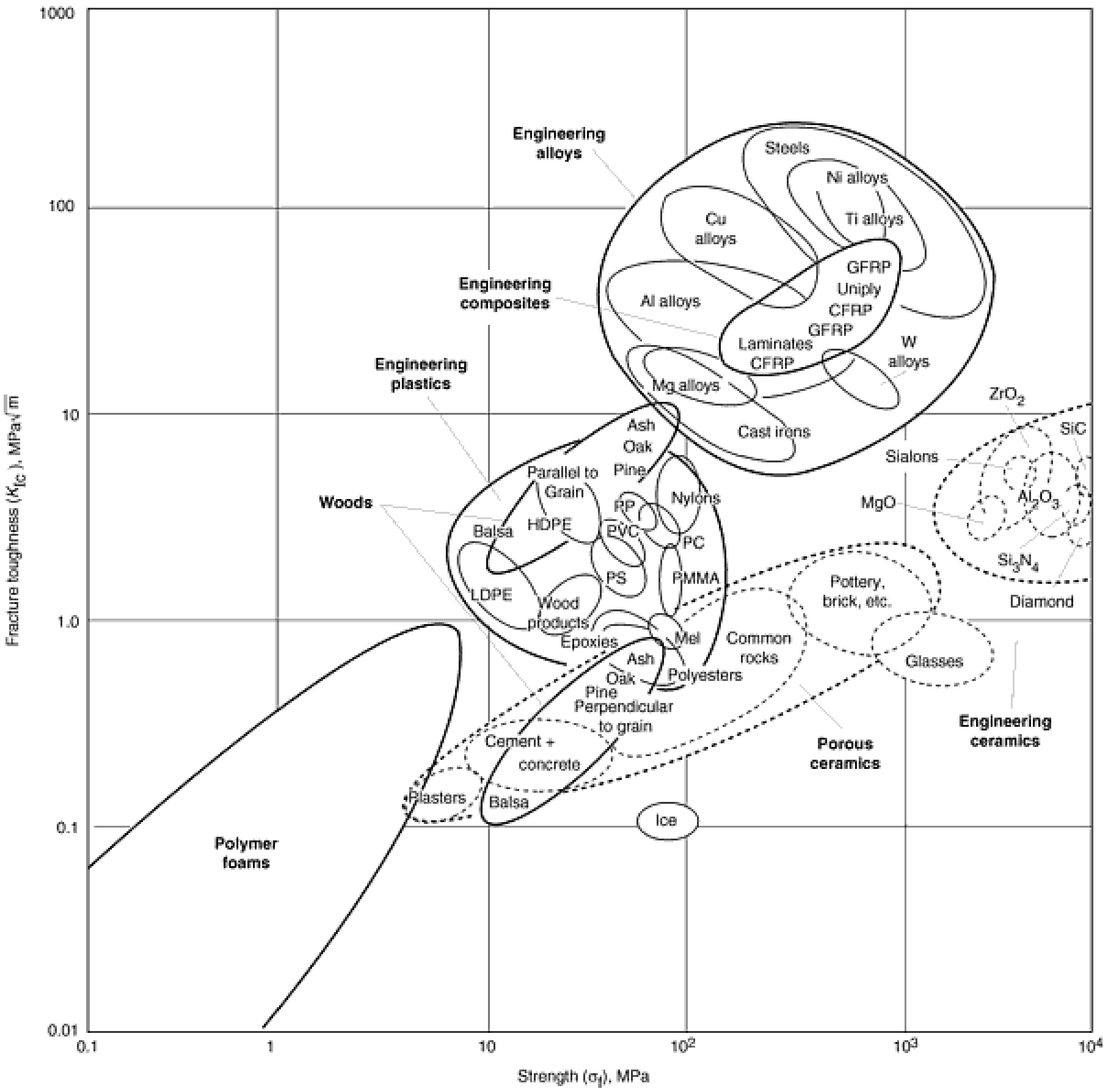


Fig. 3 Fracture toughness versus strength for various engineered materials. Strength is yield strength for metals/alloys and polymers, compressive strength for ceramics (note the broken property envelope lines), tear strength for elastomers, and tensile strength for composites. It should be noted that the tensile strength of engineering ceramics is about 15 times smaller than its compressive strength. Abbreviation key: CFRP, carbon-fiber reinforced polymer; GFRP, glass-fiber reinforced polymer; KFRP, kevlar-fiber reinforced polymer; PMMA, polymethyl methacrylate; Mel, melamines; PP, polypropylene; PC, polycarbonate; PS, polystyrene; PVC, polyvinyl chloride; HDPE, high-density polyethylene; LDPE, low-density polyethylene; PTFE, polytetrafluoroethylene; PU, polyurethane

Table 18 Conversion factors classified according to the quantity/property of interest

To convert from	to	multiply by
Angle		
degree	rad	1.745 329 E-02
Area		

in.^{2}	mm^2	6.451 600 E+02
in.^{2}	cm^2	6.451 600 E+00
in.^{2}	m^2	6.451 600 E-04
ft^2	m^2	9.290 304 E-02
Bending moment or torque		
lbf · in.	N · m	1.129 848 E-01
lbf · ft	N · m	1.355 818 E+00
kgf · m	N · m	9.806 650 E+00
ozf · in.	N · m	7.061 552 E-03
Bending moment or torque per unit length		
lbf · in./in.	N · m/m	4.448 222 E+00
lbf · ft/in.	N · m/m	5.337 866 E+01
Current density		
A/in.^{2}	A/cm^2	1.550 003 E-01
A/in.^{2}	A/mm^2	1.550 003 E-03
A/ft^2	A/m^2	1.076 400 E+01
Electricity and magnetism		
gauss	T	1.000 000 E-04
maxwell	μWb	1.000 000 E-02
mho	S	1.000 000 E+00
Oersted	A/m	7.957 700 E+01

Ω· cm	Ω· m	1.000 000 E-02
Ωcircular-mil/ft	μΩ· m	1.662 426 E-03
Energy (impact, other)		
ft · lbf	J	1.355 818 E+00
Btu (thermochemical)	J	1.054 350 E+03
cal (thermochemical)	J	4.184 000 E+00
kW · h	J	3.600 000 E+06
W · h	J	3.600 000 E+03
Flow rate		
ft^3/h	L/min	4.719 475 E-01
ft^3/min	L/min	2.831 000 E+01
gal/h	L/min	6.309 020 E-02
gal/min	L/min	3.785 412 E+00
Force		
lbf	N	4.448 222 E+00
kip (1000 lbf)	N	4.448 222 E+03
tonf	kN	8.896 443 E+00
kgf	N	9.806 650 E+00
Force per unit length		
lbf/ft	N/m	1.459 390 E+01
lbf/in.	N/m	1.751 268 E+02

Fracture toughness		
ksi $\sqrt{in}$	MPa $\sqrt{m}$	1.098 800 E+00
Heat content		
Btu/lb	kJ/kg	2.326 000 E+00
cal/g	kJ/kg	4.186 800 E+00
Heat input		
J/in.	J/m	3.937 008 E+01
kJ/in.	kJ/m	3.937 008 E+01
Length		
Å	nm	1.000 000 E-01
µin.	µm	2.540 000 E-02
mil	µm	2.540 000 E+01
in.	mm	2.540 000 E+01
in.	cm	2.540 000 E+00
ft	m	3.048 000 E-01
yd	m	9.144 000 E-01
mile	km	1.609 300 E+00
Mass		
oz	kg	2.834 952 E-02
lb	kg	4.535 924 E-01

ton (short, 2000 lb)	kg	9.071 847 E+02
ton (short, 2000 lb)	kg × $10^{3(a)}$	9.071 847 E-01
ton (long, 2240 lb)	kg	1.016 047 E+03
Mass per unit area		
oz/in.^{2}	kg/m^2	4.395 000 E+01
oz/ft^2	kg/m^2	3.051 517 E-01
oz/yd^2	kg/m^2	3.390 575 E-02
lb/ft^2	kg/m^2	4.882 428 E+00
Mass per unit length		
lb/ft	kg/m	1.488 164 E+00
lb/in.	kg/m	1.785 797 E+01
Mass per unit time		
lb/h	kg/s	1.259 979 E-04
lb/min	kg/s	7.559 873 E-03
lb/s	kg/s	4.535 924 E-01
Mass per unit volume (includes density)		
g/cm^3	kg/m^3	1.000 000 E+03
lb/ft^3	g/cm^3	1.601 846 E-02
lb/ft^3	kg/m^3	1.601 846 E+01
lb/in.^{3}	g/cm^3	2.767 990 E+01
lb/in.^{3}	kg/m^3	2.767 990 E+04

Power		
Btu/s	kW	1.055 056 E+00
Btu/min	kW	1.758 426 E-02
Btu/h	W	2.928 751 E-01
erg/s	W	1.000 000 E-07
ft · lbf/s	W	1.355 818 E+00
ft · lbf/min	W	2.259 697 E-02
ft · lbf/h	W	3.766 161 E-04
hp (550 ft · lbf/s)	kW	7.456 999 E-01
hp (electric)	kW	7.460 000 E-01
Power density		
W/in.^{2}	W/m^2	1.550 003 E+03
Pressure (fluid)		
atm (standard)	Pa	1.013 250 E+05
bar	Pa	1.000 000 E+05
in. Hg (32 °F)	Pa	3.386 380 E+03
in. Hg (60 °F)	Pa	3.376 850 E+03
lbf/in.^{2} (psi)	Pa	6.894 757 E+03
torr (mm Hg, 0 °C)	Pa	1.333 220 E+02
Specific heat		
Btu/lb · °F	J/kg · K	4.186 800 E+03

cal/g · °C	J/kg · K	4.186 800 E+03
Stress (force per unit area)		
tonf/in.^{2} (tsi)	MPa	1.378 951 E+01
kgf/mm^2	MPa	9.806 650 E+00
ksi	MPa	6.894 757 E+00
lbf/in.^{2} (psi)	MPa	6.894 757 E-03
MN/m^2	MPa	1.000 000 E+00
Temperature		
°F	°C	5/9 · (°F-32)
°R	°K	5/9
Temperature interval		
°F	°C	5/9
Thermal conductivity		
Btu · in./s · ft^2 · °F	W/m · K	5.192 204 E+02
Btu/ft · h · °F	W/m · K	1.730 735 E+00
Btu · in./h · ft^2 · °F	W/m · K	1.442 279 E-01
cal/cm · s · °C	W/m · K	4.184 000 E+02
Thermal expansion		
in./in. · °C	m/m · K	1.000 000 E+00
in./in. · °F	m/m · K	1.800 000 E+00
Velocity		

ft/h	m/s	8.466 667 E-05
ft/min	m/s	5.080 000 E-03
ft/s	m/s	3.048 000 E-01
in./s	m/s	2.540 000 E-02
km/h	m/s	2.777 778 E-01
mph	km/h	1.609 344 E+00
Velocity of rotation		
rev/min (rpm)	rad/s	1.047 164 E-01
rev/s	rad/s	6.283 185 E+00
Viscosity		
poise	Pa · s	1.000 000 E+01
strokes	m^2/s	1.000 000 E-04
ft^2/s	m^2/s	9.290 304 E-02
$in.^2/s$	mm^2/s	6.451 600 E+02
Volume		
$in.^3$	m^3	1.638 706 E-05
ft^3	m^3	2.831 685 E-02
fluid oz	m^3	2.957 353 E-05
gal (U.S. liquid)	m^3	3.785 412 E-03
Volume per unit time		
ft^3/min	m^3/s	4.719 474 E-04

ft^3/s	m^3/s	2.831 685 E-02
in.^{3}/min	m^3/s	2.731 177 E-07
Wavelength		
Å	nm	1.000 000 E-01

(a) kg × 10^3 = 1 metric tonne

Table 19 Alphabetical listing of common conversion factors

Conversion factors are written as a number greater than one and less than ten with six or fewer decimal places. This number is followed by the letter E (for exponent), a plus or minus symbol, and two digits that indicate the power of 10 by which the number must be multiplied to obtain the correct value. For example: 3.523 907 E - 02 is 3. 523 907 × 10-2 or 0.035 239 07 An asterisk (*) after the sixth decimal place indicates that the conversion factor is exact and that all subsequent digits are zero. All other conversion factors have been rounded off.

To convert from	**to**	**Multiply by**
abampere	ampere (A)	1.000 000* E+01
abcoulomb	coulomb (C)	1.000 000* E+01
abfarad	farad (F)	1.000 000* E+09
abhenry	henry (H)	1.000 000* E-09
abmho	siemens (S)	1.000 000* E+09
abohm	ohm (Ω)	1.000 000* E-09
abvolt	volt (V)	1.000 000* E-08
ampere hour	coulomb (C)	3.600 000* E+03
angstrom	meter (m)	1.000 000* E-10
atmosphere, standard	pascal (Pa)	1.013 250* E+0.5
atmosphere, technical (= 1 kgf/cm^2)	pascal (Pa)	9.806 650* E+04
bar	pascal (Pa)	1.000 000* E+05

barn	square meter (m^2)	1.000 000* E-28
barrel (for petroleum, 42 gal)	cubic meter (m^3)	1.589 873 E-01
British thermal unit (International Table)	joule (J)	1.055 056 E+03
British thermal unit (mean)	joule (J)	1.055 87 E+03
British thermal unit (thermochemical)	joule (J)	1.054 350 E+03
British thermal unit (39 °F)	joule (J)	1.059 67 E+03
British thermal unit (59 °F)	joule (J)	1.054 80 E+03
British thermal unit (60 °F)	joule (J)	1.054 68 E+03
Btu (International Table) · ft/(h · ft^2 · °F) (thermal conductivity)	watt per meter kelvin [W/(m · K)]	1.730 735 E+00
Btu (thermochemical) · ft/(h · ft^2 · °F) (thermal conductivity)	watt per meter kelvin [W/(m · K)]	1.729 577 E+00
Btu (International Table) · in./(h · ft^2 · °F) (thermal conductivity)	watt per meter kelvin [W/(m · K)]	1.442 279 E-01
Btu (thermochemical) · in./(h · ft^2 · °F) (thermal conductivity)	watt per meter kelvin [W/(m · K)]	1.441 314 E-01
Btu (International Table) · in./s · ft^2 · °F) (thermal conductivity)	watt per meter kelvin [W/(m · K)]	5.192 204 E+02
Btu (thermochemical) · in./(s · ft^2 · °F) (thermal conductivity)	watt per meter kelvin [W/(m · K)]	5.188 732 E+02
Btu (International Table)/h	watt (W)	2.930 711 E-01
Btu (International Table)/s	watt (W)	1.055 056 E+03
Btu (thermochemical)/h	watt (W)	2.928 751 E-01
Btu (thermochemical)/min	watt (W)	1.757 250 E+01
Btu (thermochemical)/s	watt (W)	1.054 350 E+03
Btu (International Table)/ft^2	joule per square meter (J/m^2)	1.135 653 E+04
Btu (thermochemical)/ft^2	joule per square meter (J/m^2)	1.134 893 E+04

Btu (International Table)/(ft^2 · s)	watt per square meter (W/m^2)	1.135 653 E+04
Btu (International Table)/(ft^2 · h)	watt per square meter (W/m^2)	3.154 591 E+00
Btu (thermochemical)/(ft^2 · h)	watt per square meter (W/m^2)	3.152 481 E+00
Btu (thermochemical)/(ft^2 · min)	watt per square meter (W/m^2)	1.891 489 E+02
Btu (thermochemical)/(ft^2 · s)	watt per square meter (W/m^2)	1.134 893 E+04
Btu (thermochemical)/(in.^{2} · s)	watt per square meter (W/m^2)	1.634 246 E+06
Btu (International Table)/(h · ft^2 · °F) (thermal conductance)	watt per square meter kelvin [W/(m^2 · K)]	5.678 263 E+00
Btu (thermochemical)/(h · ft^2 · °F) (thermal conductance)	watt per square meter kelvin [W/(m^2 · K)]	5.674 466 E+00
Btu (International Table)/(s · ft^2 · °F)	watt per square meter kelvin [W/(m^2 · K)]	2.044 175 E+04
Btu (thermochemical)/(s · ft^2 · °F)	watt per square meter kelvin [W/m^2 · K)]	2.042 808 E+04
But (International Table)/lb	joule per kilogram (J/kg)	2.326 000* E+03
Btu (thermochemical)/lb	joule per kilogram (J/kg)	2.324 444 E+03
Btu (International Table)/(lb · °F) (heat capacity)	joule per kilogram kelvin [J/(kg · K)]	4.186 800* E+03
Btu (thermochemical)/(lb · °F) (heat capacity)	joule per kilogram kelvin [J/(kg · K)]	4.184 000* E+03
Btu (International Table)/ft^3	joule per cubic meter (J/m^3)	3.725 895 E+04
Btu (thermochemical)/ft^3	joule per cubic meter (J/m^3)	3.723 402 E+04
bushel (U.S.)	cubic meter (m^3)	3.523 907 E-02
calorie (International Table)	joule (J)	4.186 800* E+00
calorie (mean)	joule (J)	4.190 02 E+00
calorie (thermochemical)	joule (J)	4.184 000* E+00
calorie (15 °C)	joule (J)	4.185 80 E+00

calorie (20 °C)	joule (J)	4.181 90 E+00
calorie (kilogram, International Table)	joule (J)	4.186800* E+03
calorie (kilogram, mean)	joule (J)	4.190 02 E+03
calorie (kilogram, thermochemical)	joule (J)	4.184 000* E+03
cal (thermochemical)/cm^2	joule per square meter (J/m^2)	4.184 000* E+04
cal (International Table)/g	joule per kilogram (J/kg)	4.186 800* E+03
cal (thermochemical)/g	joule per kilogram (J/kg)	4.184 000* E+03
cal (International Table)/(g · °C)	joule per kilogram kelvin [J/(kg · K)]	4.186 800* E+03
cal (thermochemical)/(g · °C)	joule per kilogram kelvin [J/(kg · K)]	4.184 000* E+03
cal (thermochemical)/min	watt (W)	6.973 333 E-02
cal (thermochemical)/s	watt (W)	4.184 000* E+00
cal (thermochemical)/(cm^2 · s)	watt per square meter (W/m^2)	4.184 000* E+04
cal (thermochemical)/(cm^2 · min)	watt per square meter (W/m^2)	6.973 333 E+02
cal (thermochemical)/(cm^2 · s)	watt per square meter (W/m^2)	4.184 000* E+04
cal (thermochemical)/(cm · s · °C)	watt per meter kelvin [W/(m · K)]	4.184 000* E+02
cd/in.^{2}	candela per square meter (cd/m^2)	1.550 003 E+03
carat (metric)	kilogram (kg)	2.000 000* E-04
centimeter of mercury (0 °C)	pascal (Pa)	1.333 22 E+03
centimeter of water (4 °C)	pascal (Pa)	9.806 38 E+01
centipoise (dynamic viscosity)	pascal second (Pa · s)	1.000 000* E-03
centistokes (kinematic viscosity)	square meter per second (m^2/s)	1.000 000* E-06

circular mil	square meter (m^2)	5.067 075 E-10
curie	becquerel (Bq)	3.700 000* E+10
degree (angle)	radian (rad)	1.745 329 E-02
degree Celsius	kelvin (K)	$T_K = t_{°C} + 273.15$
degree Fahrenheit	degree Celsius (°C)	$t_{°C} = (t_{°F} - 32)/1.8$
degree Fahrenheit	kelvin (K)	$T_K = (t_{°F} + 459.67)/1.8$
degree Rankine	kelvin (K)	$T_K = T_{°R}/1.8$
°F · h · ft^2/Btu (International Table) (thermal resistance)	kelvin square meter per watt (K · m^2/W)	1.761,102 E-01
°F · h · ft^2/Btu (thermochemical) (thermal resistance)	kelvin square meter per watt (K · m^2/W)	1.762 280 E-01
°F · h · ft^2/[Btu (International Table) · in.] (thermal resistivity)	kelvin meter per watt (K · m/W)	6.933 471 E+00
°F · h · ft^2/[Btu (thermochemical) · in.] (thermal resistivity)	kelvin meter per watt (K · m/W)	6.938 113 E+00
denier	kilogram per meter (kg/m)	1.111 111 E-07
dyne	newton (N)	1.000 000* E-05
dyne · cm	newton meter (N · m)	1.000 000* E-07
dyne/cm^2	pascal (Pa)	1.000 000* E-01
electronvolt	joule (J)	1.602 19 E-19
EMU (electromagnetic units) of capacitance	farad (F)	1.000 000* E+09
EMU of current	ampere (A)	1.000 000* E+01
EMU of electric potential	volt (V)	1.000 000* E-08
EMU of inductance	henry (H)	1.000 000* E-09
EMU of resistance	ohm (Ω)	1.000 000* E-09

ESU (electrostatic units) of capacitance	farad (F)	1.112 650 E-12
ESU of current	ampere (A)	3.335 6 E-10
ESU of electric potential	volt (V)	2.997 9 E+02
ESU of inductance	henry (H)	8.987 554 E+11
ESU of resistance	ohm (Ω)	8.987 554 E+11
erg	joule (J)	1.000 000* E-07
erg/(cm^2 · s)	watt per square meter (W/m^2)	1.000 000* E-03
erg/s	watt (W)	1.000 000* E-07
faraday (based on carbon-12)	coulomb (C)	9.648 70 E+04
faraday (chemical)	coulomb (C)	9.649 57 E+04
faraday (physical)	coulomb (C)	9.652 19 E+04
fluid ounce (U.S.)	cubic meter (m^3)	2.957 353 E-05
foot	meter (m)	3.048 000* E-01
ft^2	square meter (m^2)	9.290 304* E-02
ft^2/h (thermal diffusivity)	square meter per second (m^2/s)	2.580 640* E-05
ft^2/s	square meter per second (m^2/s)	9.290 304* E-02
ft^3/min	cubic meter per second (m^3/s)	4.719 474 E-04
ft^3/s	cubic meter per second (m^3/s)	2.831 685 E-02
ft/h	meter per second (m/s)	8.466 667 E-05
ft/min	meter per second (m/s)	5.080 000* E-03
ft/s	meter per second (m/s)	3.048 000* E-01

ft/s^2	meter per second squared (m/s^2)	3.048 000* E-01
footcandle	lux (lx)	1.076 391 E+01
footlambert	candela per square meter (cd/m^2)	3.426 259 E+00
ft · lbf	joule (J)	1.355 818 E+00
ft · lbf/h	watt (W)	3.766 161 E-04
ft · lbf/min	watt (W)	2.259 697 E-02
ft · lbf/s	watt (W)	1.355 818 E+00
ft-poundal	joule (J)	4.214 011 E-02
g, standard free fall	meter per second squared (m/s^2)	9.806 650* E+00
gal	meter per second squared (m/s^2)	1.00 000* E-02
gallon (Canadian liquid)	cubic meter (m^3)	4.546 090 E-03
gallon (U.K. liquid)	cubic meter (m^3)	4.546 092 E-03
gallon (U.S. dry)	cubic meter (m^3)	4.404 884 E-03
gallon (U.S. liquid)	cubic meter (m^3)	3.785 412 E-03
gallon (U.S. liquid) per day	cubic meter per second (m^3/s)	4.381 264 E-08
gallon (U.S. liquid) per minute	cubic meter per second (m^3/s)	6.309 020 E-05
gallon (U.S. liquid) per hp · h (SFC, specific fuel consumption)	cubic meter per joule (m^3/J)	1.410 089 E-09
gauss	tesla (T)	1.000 000* E-04
gilbert	ampere (A)	7.957 747 E-01
grain	kilogram (kg)	6.479 891* E-05
grain/gal (U.S. liquid)	kilogram per cubic meter (kg/m^3)	1.711 806 E-02

gram	kilogram (kg)	1.000 000* E-03
g/cm^3	kilogram per cubic meter (kg/m^3)	1.000 000* E+03
gf/cm^2	pascal (Pa)	9.806 650* E+01
hectare	square meter (m^2)	1.000 000* E+04
horsepower (550 ft · lbf/s)	watt (W)	7.456 999 E+02
horsepower (boiler)	watt (W)	9.809 50 E+03
horsepower (electric)	watt (W)	7.460 000* E+02
horsepower (metric)	watt (W)	7.354 99 E+02
horsepower (water)	watt (W)	7.460 43 E+02
horsepower (U.K.)	watt (W)	7.457 0 E+02
inch	meter	2.540 000* E-02
inch of mercury (32 °F)	pascal (Pa)	3.386 38 E+03
inch of mercury (60 °F)	pascal (Pa)	3.376 85 E+03
inch of water (39.2 °F)	pascal (Pa)	2.490 82 E+02
inch of water (60 °F)	pascal (Pa)	2.488 4 E+02
in.^{2}	square meter (m^2)	6.451 600* E-04
in.^{3} (volume)	cubic meter (m^3)	1.638 706 E-05
in.^{3}/min	cubic meter per second (m^3/s)	2.731 177 E-07
in./s	meter per second (m/s)	2.540 000* E-02
in./s^2	meter per second squared (m/s^2)	2.540 000* E-02
kelvin	degree Celsius (°C)	$t_{°C} = T_K - 273.15$

kilocalorie (International Table)	joule (J)	4.186 800* E+03
Kilocalorie (mean)	joule (J)	4.190 02 E+03
kilocalorie (thermochemical)	joule (J)	4.184 000* E+03
kilocalorie (thermochemical)/min	watt (W)	6.973 333 E+01
kilocalorie (thermochemical)/s	watt (W)	4.184 000* E+03
kilogram-force (kgf)	newton (N)	9.806 650* E+00
kgf · m	newton meter (N · m)	9.806 650* E+00
kgf · s^2/m (mass)	kilogram (kg)	9.806 650* E+00
kgf/cm^2	pascal (Pa)	9.806 650* E+04
kgf/m^2	pascal (Pa)	9.806 650* E+00
kgf/mm^2	pascal (Pa)	9.806 650* E+06
km/h	meter per second (m/s)	2.777 778 E-01
kilopond (1 kp = 1 kgf)	newton (N)	9.806 650* E+00
knot (nautical mile per hour)	meter per second (m/s)	5.144 444 E-01
kW · h	joule (J)	3.600 000* E+06
kip (1000 lbf)	newton (N)	4.448 222 E+03
kip/in.^{2} (ksi)	pascal (Pa)	6.894 757 E+06
lambert	candela per square meter (cd/m^2)	1/π* E+04
lambert	candela per square meter (cd/m^2)	3.183 099 E+03
liter	cubic meter (m^3)	1.000 000* E-03
lm/ft^2	lumen per square meter (lm/m^2)	1.076 391 E+01

maxwell	weber (Wb)	1.000 000* E-08
mho	siemens (S)	1.000 000* E+00
microinch	meter (m)	2.540 000* E-08
micron (use preferred term micrometer)	meter (m)	1.000 000* E-06
mil	meter (m)	2.540 000* E-05
mile (international)	meter (m)	1.609 344* E+03
mile (U.S. statute)	meter (m)	1.609 347 E+03
mile (international nautical)	meter (m)	1.852 000* E+03
mile (U.S. nautical)	meter (m)	1.852 000* E+03
mi^2 (international)	square meter (m^2)	2.589 988 E+06
mi^2 (U.S. statute)	square meter (m^2)	2.589 998 E+06
mi/h (international)	meter per second (m/s)	4.470 400* E-01
mi/h (international)	kilometer per hour (km/h)	1.609 344* E+00
mi/min (international)	meter per second (m/s)	2.682 240* E+01
mi/s (international)	meter per second (m/s)	1.609 344* E+03
millibar	pascal (Pa)	1.000 000* E+02
millimeter of mercury (0 °C)	pascal (Pa)	1.333 22 E+02
minute (angle)	radian (rad)	2.908 882 E-04
oersted	ampere per meter (A/m)	7.957 747 E+01
ohm centimeter	ohm meter (Ω · m)	1.000 000* E-02
ohm circular-mil per foot	ohm meter (Ω · m)	1.662 426 E-09

ounce (avoirdupois)	kilogram (kg)	2.834 952 E-02
ounce (troy or apothecary)	kilogram (kg)	3.110 348 E-02
ounce (U.K. fluid)	cubic meter (m^3)	2.841 306 E-05
ounce (U.S. fluid)	cubic meter (m^3)	2.957 353 E-05
ounce-force	newton (N)	2.780 139 E-01
ozf · in.	newton meter (N · m)	7.061 552 E-03
oz (avoirdupois)/gal (U.K. liquid)	kilogram per cubic meter (kg/m^3)	6.236 023 E+00
oz (avoirdupois)/gal (U.S. liquid)	kilogram per cubic meter (kg/m^3)	7.489 152 E+00
oz (avoirdupois)/$in.^3$	kilogram per cubic meter (kg/m^3)	1.729 994 E+03
oz (avoirdupois)/ft^2	kilogram per square meter (kg/m^2)	3.051 517 E-01
oz (avoirdupois)/yd^2	kilogram per square meter (kg/m^2)	3.390 575 E-02
pint (U.S. dry)	cubic meter (m^3)	5.506 105 E-04
pint (U.S. liquid)	cubic meter (m^3)	4.731 765 E-04
poise (absolute viscosity)	pascal second (Pa · s)	1.000 000* E-01
pound (lb avoirdupois)	kilogram (kg)	4.535 924 E-01
pound (troy or apothecary)	kilogram (kg)	3.732 417 E-01
lb · ft^2 (moment of inertia)	kilogram square meter (kg · m^2)	4.214 011 E-02
lb · $in.^2$ (moment of inertia)	kilogram square meter (kg · m^2)	2.926 397 E-04
lb/ft · h	pascal second (Pa · s)	4.133 789 E-04
lb/ft · s	pascal second (Pa · s)	1.488 164 E+00
lb/ft^2	kilogram per square meter (kg/m^2)	4.882 428 E+00

lb/ft^3	kilogram per cubic meter (kg/m^3)	1.601 846 E+01
lb/gal (U.K. liquid)	kilogram per cubic meter (kg/m^3)	9.977 637 E+01
lb/gal (U.S. liquid)	kilogram per cubic meter (kg/m^3)	1.198 264 E+02
lb/h	kilogram per second (kg/s)	1.259 979 E-04
lb/hp · h (SFC, specific fuel consumption)	kilogram per joule (kg/J)	1.689 659 E-07
lb/in.^{3}	kilogram per cubic meter (kg/m^3)	2.767 990 E+04
lb/min	kilogram per second (kg/s)	7.559 873 E-03
lb/s	kilogram per second (kg/s)	4.535 924 E-01
lb/yd^3	kilogram per cubic meter (kg/m^3)	5.932 764 E-01
poundal	newton (N)	1.382 550 E-01
poundal/ft^2	pascal (Pa)	1.488 164 E+00
poundal · s/ft^2	pascal second (Pa · s)	1.488 164 E+00
pound-force (lbf)	newton (N)	4.448 222 E+00
lbf · ft	newton meter (N · m)	1.355 818 E+00
lbf · ft/in.	newton meter (N · m)	1.355 818 E+00
lbf · in.	newton meter (N · m)	1.129 848 E-01
lbf · in./in.	newton meter per meter (N · m/m)	4.448 222 E+00
lbf · s/ft^2	pascal second (Pa · s)	4.788 026 E+01
lbf · s/in.^{2}	pascal second (Pa · s)	6.894 757 E+03
lbf/ft	newton per meter (N/m)	1.459 390 E+01
lbf/ft^2	pascal (Pa)	4.788 026 E+01

lbf/in.	newton per meter (N/m)	1.751 268 E+02
lbf/in.^{2} (psi)	pascal (Pa)	6.894 757 E+03
lbf/lb (thrust/weight [mass] ratio)	newton per kilogram (N/kg)	9.806 650 E+00
quart (U.S. dry)	cubic meter (m^3)	1.101 221 E-03
quart (U.S. liquid)	cubic meter (m^3)	9.463 529 E-04
rad (absorbed dose)	gray (Gy)	1.000 000* E-02
rem (dose equivalent)	sievert (Sv)	1.000 000* E-02
roentgen	coulomb per kilogram (C/kg)	2.58 000* E-04
rpm (r/min)	radian per second (rad/s)	1.047 198 E-01
second (angle)	radian (rad)	4.848 137 E-06
statampere	ampere (A)	3.335 640 E-10
statcoulomb	coulomb (C)	3.335 640 E-10
statfarad	farad (F)	1.112 650 E-12
stathenry	henry (H)	8.987 554 E+11
statmho	siemens (S)	1.112 650 E-12
statohm	ohm (Ω)	8.987 554 E+11
statvolt	volt (V)	2.997 925 E+02
stokes (kinematic viscosity)	square meter per second (m^2/s)	1.000 000* E-04
ton (assay)	kilogram (kg)	2.916 667 E-02
ton (long, 2240 lb)	kilogram (kg)	1.016 047 E+03
ton (metric)	kilogram (kg)	1.000 000* E+03

ton (nuclear equivalent of TNT)	joule (J)	4.184 E+09
ton (register)	cubic meter (m^3)	2.831 685 E+00
ton (short, 2000 lb)	kilogram (kg)	9.071 847 E+02
ton (long)/yd^3	kilogram per cubic meter (kg/m^3)	1.328 939 E+03
ton (short)/yd^3	kilogram per cubic meter (kg/m^3)	1.186 553 E+03
ton (short)/h	kilogram per second (kg/s)	2.519 958 E-01
ton-force (2000 lbf)	newton (N)	8.896 443 E+03
tonne	kilogram (kg)	1.000 000* E+03
torr (mmHg, 0 °C)	pascal (Pa)	1.333 22 E+02
W · h	joule (J)	3.600 000* E+03
W · s	joule (J)	1.000 000* E+00
W/cm^2	watt per square meter (W/m^2)	1.000 000* E+04
W/in.^{2}	watt per square meter (W/m^2)	1.550 003 E+03
yard	meter (m)	9.144 000* E-01
yd^2	square meter (in.^{2})	8.361 274 E-01
yd^3	cubic meter (m^3)	7.645 549 E-01
yd^3/min	cubic meter per second (m^3/s)	1.274 258 E-02

Source: Adapted from ASTM E 380, "Standard Practice for Use of the International System of Units (SI)--The Modernized Metric System"

Table 20 Conversion factors for corrosion rates

d is metal density in grams per cubic centimeter (g/cm^3)

Unit	**Factor for conversion to**					
	mdd	**g/m^2/d**	**μ/yr**	**mm/yr**	**mils/yr**	**in./yr**
Milligrams per square decimeter per day (mdd)	1	0.1	36.5/*d*	0.0365/*d*	1.144/*d*	0.00144/*d*
Grams per square meter per day (g/m^2/d)	10	1	365/*d*	0.365/*d*	14.4/*d*	0.0144/*d*
Microns per year (μm/yr)	0.0274*d*	0.00274*d*	1	0.001	0.0394	0.0000394
Millimeters per year (mm/yr)	27.4*d*	2.74*d*	1000	1	39.4	0.0394
Mils per year (mils/yr)	0.696*d*	0.0696*d*	25.4	0.0254	1	0.001
Inches per year (in./yr)	696*d*	69.6*d*	25,400	25.4	1000	1

Table 21 Fundamental physical constants

Quantity	**Symbol**	**Numerical value**[(a)]	**Units**
Speed of light (in vacuum)	c	299,792,458 (exact)	$m \cdot s^{-1}$
Electronic charge	e	1.6027733 (49)	10^{-19} C
Planck's constant	h	6.6260755 (40)	10^{-34} J · s
Avogadro constant (number)	N_A	6.0221367 (36)	10^{23} mol^{-1}
Atomic mass unit	amu or u	1.6605402 (10)	10^{-27} kg
Electron rest mass	m_e	9.1093897 (54)	10^{-31} kg
		5.4859903 (13)	10^{-4} u
Proton rest mass	m_p	1.6726231 (10)	10^{-27} kg
		1.007276470 (12)	u

Neutron rest mass	m_n	1.6749286 (10)	10^{-27} kg
		1.008664904 (14)	u
Faraday constant	F	9.6485309 (29)	10^{4} C · mol^{-1}
Electron magnetic moment	μ_e	9.2847701 (31)	10^{-24} J · T^{-1}
Molar gas constant	R	8.314510 (70)	J · mol^{-1} · K^{-1}
		8.205784 (69)	$10^{-5} m^{3}$ · atm · mol^{-1} · K^{-1}
Molar value of ideal gas at STP(b)	V_m	22.41410 (19)	
Boltzmann constant	k	1.380658 (12)	10^{-23} J · K^{-1}
Standard gravity (gravitational acceleration)	g	9.80665	m · s^{-2}
Absolute temperature	$T_{0\,°C}$	273.150 ± 0.010	*K*

Source: J. Res. National Bureau of Standards, Vol 92 (No. 2), 1987, p 85-95

(a) The numbers in parenthesis are the one-standard-deviation uncertainties in the last digits of the quoted value computed on the basis of internal consistency.

(b) STP = standard temperature and pressure (0 °C at 1 atm, or 760 torr).

Table 22 Greek alphabet

Upper and lower cases	**Name**
Α α	Alpha
Β β	Beta
Γ γ	Gamma
Δ δ ∂	Delta
Ε ε	Epsilon

Z ζ	Zeta
H η	Eta
$\Theta\theta\vartheta$	Theta
I ι	Iota
K κ	Kappa
$\Lambda\lambda$	Lambda
M μ	Mu
N ν	Nu
$\Xi\xi$	Xi
O o	Omicron
$\Pi\pi$	Pi
P ρ	Rho
$\Sigma\sigma$	Sigma
T τ	Tau
Y υ	Upsilon
$\Phi\phi\varphi$	Phi
X χ	Chi
$\Psi\psi$	Psi
ω	Omega

The Chemical Elements

Hugh Baker, Consulting Editor, ASM International

THE CHEMICAL ELEMENTS are the basic chemical substances; that is, they cannot be decomposed by chemical change or made by chemical union. These elements follow a periodic pattern related to the atomic mass of each that allows them to be arranged into a convenient table (see the periodic table shown in Fig. 1 and the corresponding Tables 1 and 2). As shown in the periodic table, most of the elements have metallic characteristics, and the table can be used to learn much about the chemical (and physical) nature of each metal.

Table 1 Names and symbols for the elements (in alphabetical order)

Name	**Symbol**
Actinium	Ac
Aluminum	Al
Americium	Am
Antimony	Sb(a)
Argon	Ar
Arsenic	As
Astatine	At
Barium	Ba
Berkelium	Bk
Beryllium	Be
Bismuth	Bi
Bohrium	Bh
Boron	B
Bromine	Br
Cadmium	Cd

Calcium	Ca
Californium	Cf
Carbon	C
Cerium	Ce
Cesium	Cs
Chlorine	Cl
Chromium	Cr
Cobalt	Co
Copper[(b)]	Cu
Curium	Cm
Dubnium	Db
Dysprosium	Dy
Einsteinium	Es
Erbium	Er
Europium	Eu
Fermium	Fm
Fluorine	F
Francium	Fr
Gadolinium	Gd
Gallium	Ga
Germanium	Ge

Gold(c)	Au
Hafnium	Hf
Hassium	Hs
Helium	He
Holmium	Ho
Hydrogen	H
Indium	In
Iodine	I
Iridium	Ir
Iron(d)	Fe
Krypton	Kr
Lanthanum	La
Lawrencium	Lr
Lead(e)	Pb
Lithium	Li
Lutetium	Lu
Magnesium	Mg
Manganese	Mn
Meitnerium	Mt
Mendelevium	Md
Mercury(f)	Hg

Molybdenum	Mo
Neodymium	Nd
Neon	Ne
Neptunium	Np
Nickel	Ni
Niobium(g)	Nb
Nitrogen	N
Nobelium	No
Osmium	Os
Oxygen	O
Palladium	Pd
Phosphorus	P
Platinum	Pt
Plutonium	Pu
Polonium	Po
Potassium(h)	K
Praseodymium	Pr
Promethium	Pm
Protactinium	Pa
Radium	Ra
Radon	Rn

Rhenium	Re
Rhodium	Rh
Rubidium	Rb
Ruthenium	Ru
Rutherfordium	Rf
Samarium	Sm
Scandium	Sc
Seaborgium	Sg
Selenium	Se
Silicon	Si
Silver(i)	Ag
Sodium(j)	Na
Strontium	Sr
Sulfur	S
Tantalum	Ta
Technetium	Tc
Tellurium	Te
Terbium	Tb
Thallium	Tl
Thorium	Th
Thulium	Tm

Tin(k)	Sn
Titanium	Ti
Tungsten(l)	W
Ununnilium	Uun
Unununium	Uuu
Uranium	U
Vanadium	V
Xenon	Xe
Ytterbium	Yb
Yttrium	Y
Zinc	Zn
Zirconium	Zr

(a) Symbol based on the Latin word *stibium.*

(b) Symbol based on the Latin word *cuprum.*

(c) Symbol based on the Latin word *aurum.*

(d) Symbol based on the Latin word *ferrum.*

(e) Symbol based on the Latin word *plumbum.*

(f) Symbol based on the Latin word *hydrargyrum.*

(g) Originally named *columbium* (Cb). In 1948, IUPAC agreed upon *niobium* as the official name.

(h) Symbol based on the Latin word *kalium.*

(i) Symbol based on the Latin word *argentum.*

(j) Symbol based on the Latin word *natrium.*

(k) Symbol based on the Latin word *stannum.*

(l) The origin of the symbol W is *wolfram,* named after the tungsten mineral *wolframite.*

Table 2 List of elements in atomic number/atomic weight order

At. No.	Symbol	Name	Atomic wt	Notes
1	H	Hydrogen	1.00794(7)	(a)(b)(c)
2	He	Helium	4.002602(2)	(a)(b)
3	Li	Lithium	6.941(2)	(a)(b)(c)(d)
4	Be	Beryllium	9.012182(3)	
5	B	Boron	10.811(7)	(a)(b)(c)
6	C	Carbon	12.0107(8)	(a)(b)
7	N	Nitrogen	14.00674(7)	(a)(b)
8	O	Oxygen	15.9994(3)	(a)(b)
9	F	Fluorine	18.9984032(5)	
10	Ne	Neon	20.1797(6)	(a)(c)
11	Na	Sodium	22.989770(2)	
12	Mg	Magnesium	24.3050(6)	
13	Al	Aluminum	26.981538(2)	
14	Si	Silicon	28.0855(3)	(b)
15	P	Phosphorus	30.973761(2)	

16	S	Sulfur	32.066(6)	(a)(b)
17	Cl	Chlorine	35.4527(9)	(c)
18	Ar	Argon	39.948(1)	(a)(b)
19	K	Potassium	39.0983(1)	(a)
20	Ca	Calcium	40.078(4)	(a)
21	Sc	Scandium	44.955910(8)	
22	Ti	Titanium	47.867(1)	
23	V	Vanadium	50.9415(1)	
24	Cr	Chromium	51.9961(6)	
25	Mn	Manganese	54.938049(9)	
26	Fe	Iron	55.845(2)	
27	Co	Cobalt	58.933200(9)	
28	Ni	Nickel	58.6934(2)	
29	Cu	Copper	63.546(3)	(b)
30	Zn	Zinc	65.39(2)	
31	Ga	Gallium	69.723(1)	
32	Ge	Germanium	72.61(2)	
33	As	Arsenic	74.92160(2)	
34	Se	Selenium	78.96(3)	
35	Br	Bromine	79.904(1)	
36	Kr	Krypton	83.80(1)	(a)(c)

37	Rb	Rubidium	85.4678(3)	(a)
38	Sr	Strontium	87.62(1)	(a)(b)
39	Y	Yttrium	88.90585(2)	
40	Zr	Zirconium	91.224(2)	(a)
41	Nb	Niobium	92.90638(2)	
42	Mo	Molybdenum	95.94(1)	(a)
43	Tc	Technetium	[98]	(e)
44	Ru	Ruthenium	101.07(2)	(a)
45	Rh	Rhodium	102.90550(2)	
46	Pd	Palladium	106.42(1)	(a)
47	Ag	Silver	107.8682(2)	(a)
48	Cd	Cadmium	112.411(8)	(a)
49	In	Indium	114.818(3)	
50	Sn	Tin	118.710(7)	(a)
51	Sb	Antimony	121.760(1)	(a)
52	Te	Tellurium	127.60(3)	(a)
53	I	Iodine	126.90447(3)	
54	Xe	Xenon	131.29(2)	(a)(c)
55	Cs	Cesium	132.90545(2)	
56	Ba	Barium	137.327(7)	
57	La	Lanthanum	138.9055(2)	(a)

58	Ce	Cerium	140.116(1)	(a)
59	Pr	Praseodymium	140.90765(2)	
60	Nd	Neodymium	144.24(3)	(a)
61	Pm	Promethium	[145]	(e)
62	Sm	Samarium	150.36(3)	(a)
63	Eu	Europium	151.964(1)	(a)
64	Gd	Gadolinium	157.25(3)	(a)
65	Tb	Terbium	158.92534(2)	
66	Dy	Dysprosium	162.50(3)	(a)
67	Ho	Holmium	164.93032(2)	
68	Er	Erbium	167.26(3)	(a)
69	Tm	Thulium	168.93421(2)	
70	Yb	Ytterbium	173.04(3)	(a)
71	Lu	Lutetium	174.967(1)	(a)
72	Hf	Hafnium	178.49(2)	
73	Ta	Tantalum	180.9479(1)	
74	W	Tungsten	184.83(1)	
75	Re	Rhenium	186.207(1)	
76	Os	Osmium	190.23(3)	(a)
77	Ir	Iridium	192.217(3)	
78	Pt	Platinum	195.078(2)	

79	Au	Gold	196.96655(2)	
80	Hg	Mercury	200.59[(a)]	
81	Tl	Thallium	204.3833(2)	
82	Pb	Lead	207.2(1)	(a)(b)
83	Bi	Bismuth	208.98038(2)	
84	Po	Polonium	[209]	(e)
85	At	Astatine	[210]	(e)
86	Rn	Radon	[222]	(e)
87	Fr	Francium	[223]	(e)
88	Ra	Radium	[226]	(e)
89	Ac	Actinium	[227]	(e)
90	Th	Thorium	232.0381(1)	(a)(e)
91	Pa	Protactinium	231.03588(2)	(e)
92	U	Uranium	238.0289(1)	(a)(c)(e)
93	Np	Neptunium	[237]	(e)
94	Pu	Plutonium	[244]	(e)
95	Am	Americium	[243]	(e)
96	Cm	Curium	[247]	(e)
97	Bk	Berkelium	[247]	(e)
98	Cf	Californium	[251]	(e)
99	Es	Einsteinium	[252]	(e)

100	Fm	Fermium	[257]	(e)
101	Md	Mendelevium	[258]	(e)
102	No	Nobelium	[259]	(e)
103	Lr	Lawrencium	[262]	(e)
104	Rf	Rutherfordium	[261]	(e)(f)
105	Db	Dubnium	[262]	(e)(f)
106	Sg	Seaborgium	[263]	(e)(f)
107	Bh	Bohrium	[262]	(e)(f)
108	Hs	Hassium	[265]	(e)(f)
109	Mt	Meitnerium	[266]	(e)(f)
110	Uun	Ununnilium	[269]	(e)(f)
111	Uuu	Unununium	[272]	(e)(f)

The data were obtained from the IUPAC Commission on Atomic Weights and Isotopic Abundances. More detailed information can be obtained by referring to *Pure Appl. Chem.,* Vol. 68, 1996, p 2339-2359.

(a) Geological specimens are known in which the element has an isotopic composition outside the limits for normal material. The difference between the atomic weight of the element in such specimens and that given in the table may exceed the stated uncertainty.

(b) Range in isotopic composition of normal terrestrial material prevents a more precise value being given; the tabulated value should be applicable to any normal material.

(c) Modified isotopic compositions may be found in commercially available material because it has been subject to an undisclosed or inadvertent isotopic fractionation. Substantial deviations in atomic weight of the element from that given in the table can occur.

(d) Commercially available Li materials have atomic weights that range between 6.94 and 6.99; if a more accurate value is required, it must be determined for the specific material.

(e) Element has no stable nuclides. The value enclosed in brackets, for example, [209], indicates the mass number of the longest-lived isotope of the element. However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

(f) The names and symbols for elements 110-111 are under review. The temporary system recommended by J. Chatt, *Pure Appl. Chem.,* Vol 51, 1979, p 381-384 is used above. The names of elements 101 to 109 were confirmed at the IUPAC General Assembly held in Geneva (press release 30 Aug 1997).

Metals — Semi-metals — Nonmetals

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	IUPAC 1988
Group	IA	IIA	IIIA	IVA	VA	VIA	VIIA		VIIIA		IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIIIB	IUPAC 1970
	IA	IIA	IIIB	IVB	VB	VIB	VIIB		VIIIB		IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA	Previous CAS
1	**1** +1 **H** −1 1.00794 1																	**2** 0 **He** 4.002602 2	K
2	**3** +1 **Li** 6.941 2-1	**4** +2 **Be** 9.0122 2-2											**5** +3 **B** 10.811 2-3	**6** +2 **C** +4 −4 12.0107 2-4	**7** +1 +5 **N** +2 −1 +3 −2 +4 −3 14.00674 2-5	**8** −2 **O** 15.9994 2-6	**9** −1 **F** 18.998403 2-7	**10** 0 **Ne** 20.1797 2-8	K-L
3	**11** +1 **Na** 22.98977 2-8-1	**12** +2 **Mg** 24.3050 2-8-2											**13** +3 **Al** 26.98154 2-8-3	**14** +2 **Si** +4 −4 28.0856 2-8-4	**15** +3 **P** +5 −3 30.97376 2-8-5	**16** +4 **S** +6 −2 32.066 2-8-6	**17** +1 **Cl** +5 +7 −1 35.4527 2-8-7	**18** 0 **Ar** 39.948 2-8-8	K-L-M
4	**19** +1 **K** 39.0983 -8-8-1	**20** +2 **Ca** 40.078 -8-8-2	**21** +3 **Sc** 44.95591 -8-9-2	**22** +2 **Ti** +3 +4 47.867 -8-10-2	**23** +2 **V** +3 +4 +5 50.9415 -8-11-2	**24** +2 **Cr** +3 +6 51.9961 -8-13-1	**25** +2 **Mn** +3 +4 +7 54.9380 -8-13-2	**26** +2 **Fe** +3 55.845 -8-14-2	**27** +2 **Co** +3 58.9332 -8-15-2	**28** +2 **Ni** +3 58.6934 -8-16-2	**29** +1 **Cu** +2 63.546 -8-18-1	**30** +2 **Zn** 65.39 -8-18-2	**31** +3 **Ga** 69.723 -8-18-3	**32** +2 **Ge** +4 72.61 -8-18-4	**33** +3 **As** +5 −3 74.9216 -8-18-5	**34** +4 **Se** +6 −2 78.96 -8-18-6	**35** +1 **Br** +5 −1 79.904 -8-18-7	**36** 0 **Kr** 83.80 -8-18-8	-L-M-N
5	**37** +1 **Rb** 85.4678 -18-8-1	**38** +2 **Sr** 87.62 -18-8-2	**39** +3 **Y** 88.90585 -18-9-2	**40** +4 **Zr** 91.224 -18-10-2	**41** +3 **Nb** +5 92.90638 -18-12-1	**42** +6 **Mo** 95.94 -18-13-1	**43** +4 **Tc** +6 +7 (98) -18-13-2	**44** +3 **Ru** 101.07 -18-15-1	**45** +3 **Rh** 102.9055 -18-16-1	**46** +2 **Pd** +4 106.42 -18-18-0	**47** +1 **Ag** 107.8682 -18-18-1	**48** +2 **Cd** 112.411 -18-18-2	**49** +3 **In** 114.818 -18-18-3	**50** +2 **Sn** +4 118.71 -18-18-4	**51** +3 **Sb** +5 −1 121.76 -18-18-5	**52** +4 **Te** +6 −2 127.60 -18-18-6	**53** +1 **I** +5 +7 −3 126.90447 -18-18-7	**54** 0 **Xe** 131.29 -18-18-8	-M-N-O
6	**55** +1 **Cs** 132.90545 -18-8-1	**56** +2 **Ba** 17.327 -18-8-2	La-Lu	**72** +4 **Hf** 178.49 -32-10-2	**73** +5 **Ta** 180.9479 -32-11-2	**74** +6 **W** 183.84 -32-12-2	**75** +4 **Re** +6 +7 186.207 -32-13-2	**76** +3 **Os** +4 190.73 -32-14-2	**77** +3 **Ir** +4 192.217 -32-15-2	**78** +2 **Pt** +4 195.078 -32-16-2	**79** +1 **Au** +3 196.9665 -32-18-1	**80** +1 **Hg** +2 200.59 -32-18-2	**81** +1 **Tl** +3 204.3833 -32-18-3	**82** +2 **Pb** +4 207.2 -32-18-4	**83** +3 **Bi** +5 208.98038 -32-18-5	**84** +2 **Po** +4 [209] -32-18-6	**85** **At** [210] -32-18-7	**86** 0 **Rn** [222] -32-18-8	-N-O-P
7	**87** +1 **Fr** [223] -18-8-1	**88** +2 **Ra** [226] -18-8-2	Ac-Lr	**104** +4 **Rf** [261] -32-10-2	**105** **Db** [262] -32-11-2	**106** **Sg** [263] -32-12-2	**107** **Bh** [262] -32-13-2	**108** **Hs** [265] -32-14-2	**109** **Mt** [266] -32-15-2	**110** **Uun** [269] -32-16-2	**111** **Uuu** [272] -32-18-1								-O-P-Q
Period	Alkali metals	Alkaline earth metals													Pnicogens	Chalcogens	Halogens	Noble gases	Electron orbit

Key to chart

Atomic number → **50** +2 ← Oxidation states
Symbol → **Sn** +4
Atomic weight → 118.71
-18-18-4 ← Electron configuration

Transition elements

Lanthanides	**57** +3 **La** 138.9055 -18-9-2	**58** +3 **Ce** +4 140.116 -20-8-2	**59** +3 **Pr** 140.9077 -21-8-2	**60** +3 **Nd** 144.24 -22-8-2	**61** +3 **Pm** [145] -23-8-2	**62** +2 **Sm** +3 150.36 -24-8-2	**63** +2 **Eu** +3 151.964 -25-8-2	**64** +3 **Gd** 157.25 -25-9-2	**65** +3 **Tb** 158.92534 -27-8-2	**66** +3 **Dy** 162.50 -28-8-2	**67** +3 **Ho** 164.9303 -29-8-2	**68** +3 **Er** 167.26 -30-8-2	**69** +3 **Tm** 168.93421 -31-8-2	**70** +2 **Yb** +3 173.04 -32-8-2	**71** +3 **Lu** 174.967 -32-9-2	-N-O-P
Actinides	**89** +3 **Ac** [227] -18-9-2	**90** +4 **Th** 232.0381 -18-10-2	**91** +5 **Pa** +4 231.0359 -20-9-2	**92** +3 **U** +4 +5 +6 238.0289 -21-9-2	**93** +3 **Np** +4 +5 +6 [237] -22-9-2	**94** +3 **Pu** +4 +5 +6 [244] -24-8-2	**95** +3 **Am** +4 +5 +6 [243] -25-8-2	**96** +3 **Cm** [247] -25-9-2	**97** +3 **Bk** +4 [247] -27-8-2	**98** +3 **Cf** [251] -28-8-2	**99** +3 **Es** [252] -29-8-2	**100** +3 **Fm** [257] -30-8-2	**101** +2 **Md** +3 [258] -31-8-2	**102** +2 **No** +3 [259] -32-8-2	**103** +3 **Lr** [262] -32-9-2	-O-P-Q

Fig. 1 Periodic table of the elements. Values in brackets indicate the mass number of the longest lived isotope of the radioactive element.

In the periodic table (Fig. 1), the elements are arranged in the order of increasing *atomic number* (the number of protons in the nucleus), but those that have the same number of electrons inhabiting their outermost electron shells (and, therefore, having similar chemical behavior) are grouped under each other; hence, the vertical columns of related elements in the periodic table are called *groups.* As atomic number increases, more orbital electrons must be accommodated in the shells, and as each outermost shell is filled a new outermost shell (and a new *period* of the table) is begun. Because the additional shells are larger than the preceding shells, there is room for more electrons and the periods get longer: from two (period 1) to eight and eight (periods 2 and 3), then to eighteen and eighteen (periods 4 and 5), and finally to thirty-two and (probably) thirty-two (periods 6 and 7).

Over the years, various conventions have been used to identify each group in the periodic table. For example, the 1948 Edition of the *Metals Handbook* used a system similar to that adopted by the International Union of Pure and Applied Chemistry (IUPAC) in 1970 in which the left-side and right-side elements in periods 4 through 7 are distinguished by the addition of the letters "A" and "B," respectively (see Fig. 1), the only difference being that the Handbook used small (lower-case) letters with the Roman numerals rather than capital (upper-case) letters. In contrast to the 1970 IUPAC system, which was commonly used in Europe, the Chemical Abstracts Service (CAS) of the American Chemical Society and many other U.S. chemists applied the "B" to the additional groups (groups 3 through 12) in periods 4 through 7 and "A" to the rest. Other conventions that have been occasionally followed in the past are to use "0" instead of VIIIA or VIIIB to identify group 18, and to use Arabic numerals instead of Roman numerals. The most recent (1988) IUPAC recommendation is to eliminate both practices and to use Arabic numerals 1 through 18 instead.

Another common practice is to identify groups of similar elements with collective names. For example, the elements lithium, sodium, potassium, rubidium, cesium, and francium in group 1 are called *alkali metals* from the Arabic for "the ashes" (hydrogen, which is not normally a solid, is not included), and all the elements in group 2 are called *alkaline earth metals.* While not yet approved by IUPAC, the term *pnicogens* or *pnictides* has been applied to the elements in group 15; the term is from the Greek for "stifle, choke, or strangle," which alludes to nitrogen, that is, "burnt air." The term *chalcogens* has been applied to group 16 elements; the term is from the Greek for "copper," which first alluded to the common occurrence of oxygen and sulfur in many copper ores, but later referred to all these elements that were "ore formers." The term *halogens* (from the Greek for "salt") has been applied to group 17, and the elements in group 18 are called *noble gases* or *inert gases.* Sometimes hydrogen is positioned at the top of the halogen group in addition to its normal position at the top of group 1.

Rows of some similar elements are similarly named. For example, the elements in rows 3 through 10, whose atoms have an incomplete *d* subshell of electrons, are called *transition elements* or *transition metals.* IUPAC 1988, however, also includes the atoms in row 11 in the group of transition elements, while other organizations include *all* the elements between rows 2 and 12. The elements lanthanum through lutetium (atomic numbers 57 through 71) are termed *lanthanide elements, lanthanide metals,* or simply *lanthanides.* The lanthanides together with group 3 elements yttrium (atomic number 39) and scandium (atomic number 21) are called *rare earth elements, rare earth metals,* or simply *rare earths.* The elements actinium through lawrencium (atomic numbers 89 through 103) are similarly termed *actinide elements, actinide metals,* or simply *actinides* (or sometimes second-series rare earths), while those from thorium (atomic number 90) through lawrencium (atomic number 103) are termed *actinoids.*

As stated earlier, most of the chemical elements are *metals.* (The word "metal" is derived from the Greek "metallon," which is believed to have originated in a verb meaning to seek, search after, or inquire about.) In modern science, a metal is any element that tends to lose electrons from the outer shells of its atoms, with the resulting positive ions held together in a unique crystal structure by the cloud of these free electrons in a mechanism that has been called *metallic bonding.* This type of atomic bonding is in contrast to ionic bonding and to covalent bonding. In *ionic bonding,* transfer of valence (outer shell) electrons between dissimilar atoms produces stable outer shells in each and results in positive and negative ions that are mutually attracted by coulombic forces, but do not form a crystal. In *covalent bonding,* valence electrons are shared, rather than exchanged, and a nonmetallic crystal can form, for example, the diamond form of carbon.

The cloud of free electrons in metallic crystals gives rise to the three physical characteristics typical of solid metals: metals are good conductors of electricity, good conductors of heat, and they have a lustrous appearance. In addition, most elemental metals are malleable, ductile, generally denser than other elemental substances, and usually form positive ions. Those elements that do not display the characteristics of the metallic elements are called *nonmetals* (see the periodic table). However, there are some elements that act as metals under some circumstances and act like nonmetals underdifferent circumstances. These are now called *semimetals,* but have been called *metalloids* (like metals). As shown, the boundaries separating the regions in the periodic table covered by the three classes of elements are not distinct except that nonmetals never form positive ions.

Crystal Structure of Metallic Elements

Hugh Baker, Consulting Editor, ASM International

Introduction

CRYSTAL STRUCTURE, as defined broadly, is the arrangement of atoms or molecules in the solid state. Crystal structure also involves consideration of defects, or abnormalities, in the idealized atomic/molecular arrangements. The collective arrangement of these atoms on a scale much greater than that of the individual atom is referred to as the microstructure of the material.

This article briefly reviews the terms and basic concepts associated with crystal structures that have been widely studied and are of the most importance to metallurgists. More detailed information on the crystal structure of metals can be found in Volume 9, *Metallography and Microstructures,* of the *ASM Handbook* and in the Selected References listed at the conclusion of this article.

Crystallographic Terms and Basic Concepts

A *crystal* is a solid consisting of atoms or molecules arranged in a pattern that is repetitive in three dimensions. The arrangement of the atoms or molecules in the interior of a crystal is called its *crystal structure.* The *unit cell* of a crystal is the smallest pattern of arrangement that can be contained in a parallelepiped, the edges of which form the *a, b,* and *c* axes of the crystal. The three-dimensional aggregation of unit cells in the crystal forms a *space lattice,* or *Bravais lattice* (see Fig. 1).

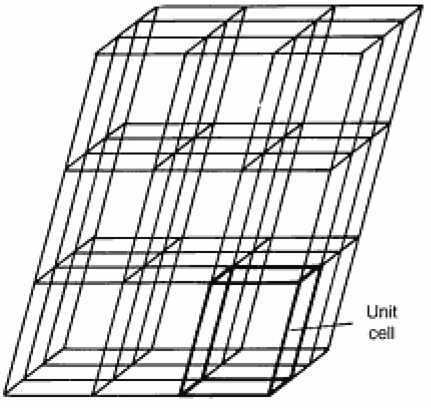


Fig. 1 A space lattice. (Bold lines outline a unit cell.)

Crystal Systems. Seven different *crystal systems* are recognized in crystallography, each having a different set of axes, unit-cell edge lengths, and interaxial angles (see Table 1). Unit-cell *edge lengths a, b,* and *c* are measured along the corresponding *a, b,* and *c* axes (see Fig. 2). Unit-cell faces are identified by capital letters: face *A* contains axes *b* and *c,* face *B* contains *c* and *a,* and face *C* contains *a* and *b.* (Faces are not labeled in Fig. 2.) Interaxial angle α occurs in face *A,* angle βin face *B,* and angle γin face *C* (see Fig. 2).

Table 1 Relationships of edge lengths and of interaxial angles for the seven crystal systems

Crystal system	**Edge lengths**	**Interaxial angles**	**Examples**
Triclinic (anorthic)	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90°$	HgK
Monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90° \neq \beta$	βS; $CoSb_2$
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90°$	αS; Ga; Fe_3C (cementite)
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90°$	βSn (white): TiO_2
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90°; \gamma = 120°$	Zn; Cd; NiAs
Rhombohedral[(a)]	$a = b = c$	$\alpha = \beta = \gamma = 90°$	As; Sb; Bi; calcite
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90°$	Cu; Ag; Au; Fe; NaCl

(a) Rhombohedral crystals (sometimes called trigonal) also can be described by using hexagonal axes (rhombohedral-hexagonal).

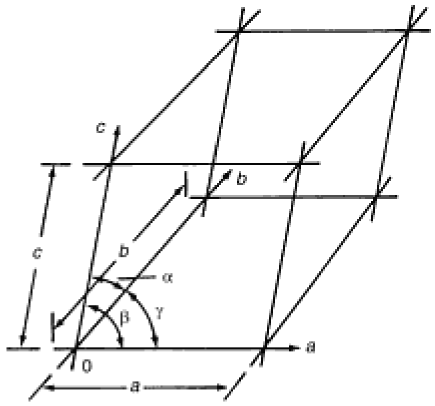


Fig. 2 Crystal axes and unit-cell edge lengths. (Unit-cell faces are shown in the illustration, but to avoid confusion, they are not labeled.)

Lattice Dimensions. It should be noted that the unit-cell edge lengths and interaxial angles are unique for each crystalline substance. The unique edge lengths are called *lattice parameters.* The term *lattice constant* also has been used for the length of an edge, but the values of edge length are not constant, varying with composition within a phase field and also with temperature due to thermal expansion and contraction. (Reported lattice-parameter values are assumed to be room-temperature values unless otherwise specified.) Interaxial angles other than 90° or 120° also can change slightly with changes in composition. When the edges of the unit cell are not equal in all three directions, all unequal lengths must be stated to completely define the crystal. The same is true if all interaxial angles are not equal. When defining the unit-cell size of an alloy phase, the possibility of crystal ordering occurring over several unit cells should be considered.

Lattice Points. As shown in Fig. 1, a space lattice can be viewed as a three-dimensional network of straight lines. The intersections of the lines (called *lattice points*) represent locations in space for the same kind of atom or group of atoms of identical composition, arrangement, and orientation. There are five basic arrangements for lattice points within a unit cell. The first four are: primitive (simple), having lattice points solely at cell corners; base-face centered (end-centered), having lattice points centered on the *C* faces, or ends of the cell; all-face centered, having lattice points centered on all faces; and innercentered (body-centered), having lattice points at the center of the volume of the unit cell. The fifth arrangement, the primitive rhombohedral unit cell, is considered a separate basic arrangement, as shown in the following section on crystal-structure nomenclature. These five basic arrangements are identified by capital letters as follows: *P* for the primitive cubic, *C* for the cubic cell with lattice points on the two *C* faces, *F* for all-face-centered cubic, *I* for innercentered (body-centered) cubic, and *R* for primitive rhombohedral.

Crystal-Structure Nomenclature. When the seven crystal systems are considered together with the five space lattices, the combinations listed in Table 2 and shown in Fig. 3 are obtained. These fourteen combinations form the basis of the system of *Pearson symbols* developed by William B. Pearson, which are widely used to identify crystal types. As can be seen in the table, the Pearson symbol uses a small letter to identify the crystal system and a capital letter to identify the space lattice. To these is added a number equal to the number of atoms in the unit cell conventionally selected for the particular crystal type. When determining the number of atoms in the unit cell, it should be remembered that each atom that is shared with an adjacent cell (or cells) must be counted as only a fraction of an atom. The Pearson symbols for some simple metal crystals are shown in Fig. 4, along with schematics illustrating the atom arrangements in the unit cell.

Table 2 The 14-space (Bravais) lattices and their Pearson symbols (see also Fig. 2)

Crystal system	Space lattice	Pearson symbol
Triclinic (anorthic)	Primitive	*aP*
Monoclinic	Primitive	*mP*
	Base centered[(a)]	*mC*
Orthorhombic	Primitive	*oP*
	Base centered[(a)]	*oC*
	Body centered	*oI*
	Face centered	*oF*
Tetragonal	Primitive	*tP*
	Body centered	*tI*
Hexagonal	Primitive	*hP*
Rhombohedral	Primitive	*hR*
Cubic	Primitive	*cP*

	Body centered	*cI*
	Face centered	*cF*

(a) The face that has a lattice point at its center may be chosen as the *c* face (the *xy* plane), denoted by the symbol *C*, or as the *a* or *b* face, denoted by *A* or *B*, because the choice of axes is arbitrary and does not alter the actual translations of the lattice.

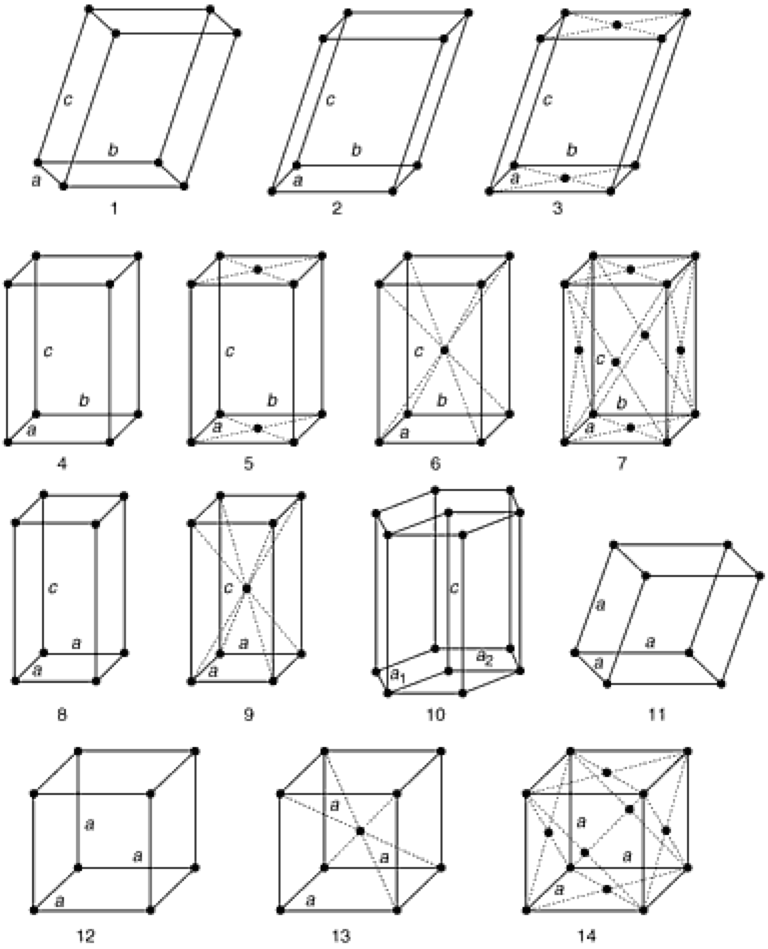
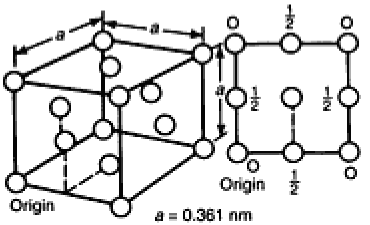


Fig. 3 The 14-space (Bravais) lattices illustrated by a unit cell of each: (1) triclinic, primitive; (2) monoclinic, primitive; (3) monoclinic, base centered; (4) orthorhombic, primitive; (5) orthorhombic, base centered; (6) orthorhombic, body centered; (7) orthorhombic, face centered; (8) tetragonal, primitive; (9) tetragonal, body centered; (10) hexagonal, primitive; (11) rhombohedral, primitive; (12) cubic, primitive; (13) cubic, body centered; (14) cubic, face centered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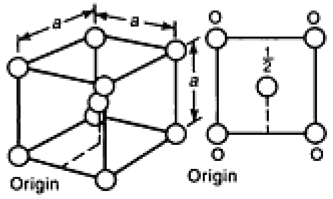
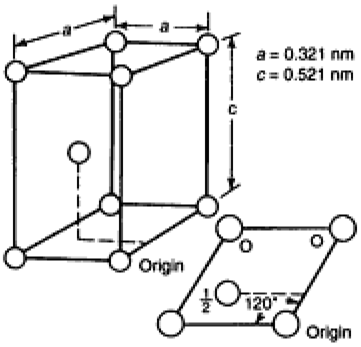
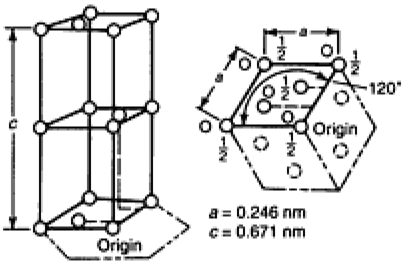
Origin
1/2

$a = 0.361$ nm
Face-centered cubic: Fm$\bar{3}$m, Cu
cF4


a
a
a
1/2
Origin
Origin

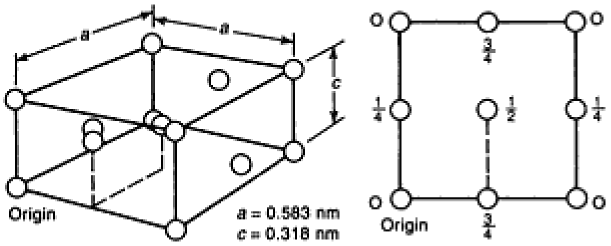
$a = 0.316$ nm
Body-centered cubic: Im$\bar{3}$m, W
cI2


a
a
$a = 0.321$ nm
$c = 0.521$ nm
c
Origin
1/2
120°
Origin


c
Origin
a
a
1/2
1/2
1/2
120°
1/2
Origin
1/2
1/2
$a = 0.246$ nm
$c = 0.671$ nm

Hexagonal: P6_3/mmc, C (graphite)
hP4

Close-packed hexagonal: P6_3/mmc, Mg
hP2


a
a
c
Origin
$a = 0.583$ nm
$c = 0.318$ nm
3/4
1/4
1/2
1/4
Origin
3/4

Body-centered tetragonal: I4_1/amd, βSn
tI4

Fig. 4 Unit cells and atom positions for some simple metal crystals. Also listed are the space lattice and crystal system, space- group notation, and prototype for each crystal. The lattice parameters reported are for the prototype crystal. In order to show the atom arrangements more clearly, the atoms in these drawings are shown much smaller than their true effective size in real crystals.

Several of the many possible crystal structures possible are so commonly found in metallic systems that they are often identified by three-letter abbreviations that combine the space lattice with crystal system. For example, bcc for body-centered cubic (two atoms per unit cell), fcc is used for face-centered cubic (four atoms per unit cell), and cph for close-packed hexagonal (two atoms per unit cell). (The latter space-lattice/crystal system is also commonly referred to as hexagonal close-packed, hcp, in metallurgical literature.)

It should be noted that in the schematic representations shown in Fig. 4, the different kinds of atoms in the prototype crystal illustrated are drawn to represent their relative sizes, but in order to show the arrangements more clearly, all the atoms are shown much smaller than their true effective size in real crystals. A more true representation of the effective diameters of the atoms in a unit cell is shown in Fig. 5 for three common crystals.

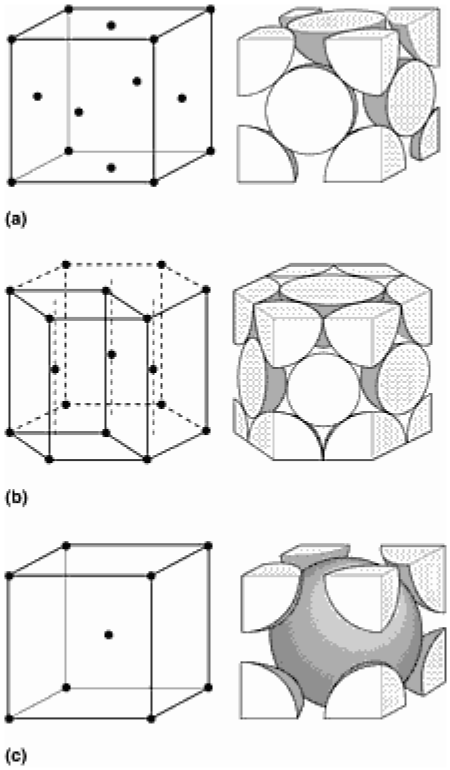


Fig. 5 Unit cells and atom positions for (a) face-centered cubic, (b) close-packed hexagonal, and (c) body-centered cubic unit cells. The positions of the atoms are shown as dots at the left of each pair of drawings, while the atoms themselves are shown close to their true effective size by spheres or portions of spheres at the right of each pair.

Each atom arrangement shown in Fig. 4 (and all other arrangements) is characterized by efficient atom packing and a high *coordination number*, which is the number of nearest neighbors surrounding each atom in the cell. Both the fcc and cph structures have a coordination number of 12, while for bcc it is 8 (plus 6 additional neighbors only slightly farther distant).

Space-group notation is a symbolic description of the space lattice and symmetry of a crystal. It consists of the symbol for the space lattice followed by letters and numbers that designate the symmetry of the crystal. The space-group notation for each unit cell illustrated in Fig. 4 is identified next to it.

To assist in classification and identification, each crystal-structure type is assigned a representative substance (element or phase) having that structure. The substance selected is called the *structure prototype* for that structure. Generally accepted prototypes for some metal crystals are listed in Fig. 4.

Many metals, and some nonmetals, exist in more than one crystalline form, a phenomenon known as *polymorphism.* When found in elemental solids, the condition is known as *allotropy*. The prevailing crystal structure depends on both the temperature and external pressure. For example, at atmospheric pressure, iron is bcc at temperatures below 912 °C (1674 °F), fcc between 912 and 1394 °C (1674 and 2541 °F), and above 1394 °C iron reverts to the bcc form until melting at 1538 °C (2800 °F). Titanium, zirconium, and hafnium all exhibit a transition from a cph structure to bcc on heating. Another familiar example is carbon: hexagonal graphite is the stable allotrope at ambient conditions, whereas the fcc allotrope diamond is formed at extremely high pressures. Crystallographic information for the allotropes of the metallic elements can be found in Table 3. Here the data are presented in terms of the Pearson symbol, space group, and prototype of the structure. Low-temperature structures are included for the diatomic and rare gases, which show many similarities with respect to the metallic elements.

Table 3 Crystal structures and lattice parameters of allotropes of the metallic elements

Element	**Temperature, °C**	**Pressure[(a)], GPa**	**Pearson symbol**	**Space group**	**Prototype**	**Lattice parameters[(b)], nm**			**Comment, *c/a*, or α or β**
						a	***b***	***c***	
Ac	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.5311	. . .	. . .	. . .
Ag	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.40857	. . .	. . .	. . .
αAl	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.40496	. . .	. . .	. . .
βAl	25	>20.5	*hP*2	$P6_3/mmc$	Mg	0.2693	. . .	0.4398	1.6331
αAm	25	atm	*hP*4	$P6_3/mmc$	αLa	0.34681	. . .	1.1241	2 × 1.621
βAm	>769	atm	*cF*4	$Fm\bar{3}m$	Cu	0.4894	. . .	. . .	. . .
γAm	>1077	atm	*cI*2	$Im\bar{3}m$	W	?	. . .	. . .	. . .
δAm	25	>15	*oC*4	*Cmcm*	αU	0.3063	0.5968	0.5169	. . .
αAr	< -189.2	atm	*cF*4	$Fm\bar{3}m$	Cu	0.53109	. . .	. . .	. . .
As	25	atm	*hR*2	$R\bar{3}m$	αAs	0.41319	. . .	. . .	α= 65.12°
Au	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.40782	. . .	. . .	. . .
βB	25	atm	*hR*105	$R\bar{3}m$	βB	1.017	. . .	. . .	a = 65.12°
αBa	25	atm	*cI*2	$\mathrm{Im}\bar{3}\mathrm{m}$	W	0.50227	. . .	. . .	. . .
βBa	25	>5.33	*hP*2	$P6_3/mmc$	Mg	0.3901	. . .	0.6154	1.5775
γBa	25	>23	?	?	. . .	. . .	. . .	. . .	. . .
αBe	25	atm	*hP*2	$P6_3/mmc$	Mg	0.22859	. . .	0.35845	1.5681

β_{Be}	>1270	atm	*cI*2	$Im\bar{3}m$	W	0.25515	. . .	. . .	. . .
BeII	25	>28.3	*hP**	. . .	. . .	0.4328	. . .	0.3416	0.7893
αBi	25	atm	*hR*2	$R\bar{3}m$	αAs	0.47460	. . .	. . .	α= 57.23°
β_{Bi}	25	>2.6	*mC*4	*C*2/*m*	β_{Bi}	0.6674	0.6117	0.3304	β= 110.33°
γ_{Bi}	25	>3.0	*mP*4	$P2_1/m$	. . .	0.665	0.420	0.465	β= 85.33°
δ_{Bi}	25	>4.3	?	?	. . .	. . .	. . .	. . .	. . .
ζ_{Bi}	25	>9.0	*cI*2	$Im\bar{3}m$	W	0.3800	. . .	. . .	. . .
αBk	25	atm	*hP*4	$P6_3/mmc$	αLa	0.3416	. . .	1.1069	2 × 1.620
β_{Bk}	>977	atm	*cF*4	$Fm\bar{3}m$	Cu	0.4997	. . .	. . .	. . .
Br	< -7.25	atm	*oC*8	*Cmca*	I_2	0.668	0.449	0.874	. . .
C(graphite)	25	atm	*hP*4	$P6_3/mmc$	C(graphite)	0.24612	. . .	0.6709	2.7258
C(diamond)	25	>60	*cF*8	$Fd\bar{3}m$	C(diamond)	0.35669	. . .	. . .	. . .
αCa	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.55884	. . .	. . .	. . .
β_{Ca}	>443	atm	*cI*2	$Im\bar{3}m$	W	0.4480	. . .	. . .	. . .
γ_{Ca}	25	>1.5	?	. . .	. . .	. . .	. . .	. . .	. . .
Cd	25	atm	*hP*2	$P6_3/mmc$	Mg	0.29793	. . .	0.56196	1.8862
αCe	< -177	atm	*cF*4	$Fm\bar{3}m$	Cu	0.485	. . .	. . .	. . .
β_{Ce}	25	atm	*hP*4	$P6_3/mmc$	αLa	0.36810	. . .	1.1857	2 × 1.611
γ_{Ce}	>61	atm	*cF*4	$Fm\bar{3}m$	Cu	0.51610	. . .	. . .	. . .

δCe	>726	atm	*cI*2	$Im\bar{3}m$	W	0.412	. . .	. . .	. . .
α'Ce	25	>5.4	*oC*4	*Cmcm*	αU	0.3049	0.5998	0.5215	. . .
αCf	25	atm	*hP*4	$P6_3/mmc$	αLa	0.339	. . .	1.1015	2 × 1.625
β_{Cf}	>590	atm	*cF*4	$Fm\bar{3}m$	Cu	?	. . .	. . .	. . .
Cl	< -100.97	atm	*oC*8	*Cmca*	I_2	0.624	0.448	0.826	. . .
αCm	25	atm	*hP*4	$P6_3/mmc$	αLa	0.3496	. . .	1.1331	2 × 1.621
β_{Cm}	>1277	atm	*cF*4	$Fm\bar{3}m$	Cu	0.4382	. . .	. . .	. . .
εCo	25	atm	*hP*2	$P6_3/mmc$	Mg	0.25071	. . .	0.40686	1.6228
αCo	>422	atm	*cF*4	$Fm\bar{3}m$	Cu	0.35447	. . .	. . .	. . .
αCr	25	atm	*cI*2	$Im\bar{3}m$	W	0.28848	. . .	. . .	. . .
α'Cr	25	HP	*tI*2	*I*4/*mmm*	α'Cr	0.2882	. . .	0.2887	1.002
αCs	25	atm	*cI*2	$Im\bar{3}m$	W	0.6141	. . .	. . .	. . .
β_{Cs}	25	>2.37	*cF*4	$Fm\bar{3}m$	Cu	0.6465	. . .	. . .	. . .
$\beta_{\mathrm{'Cs}}$	25	>4.22	*cF*4	$Fm\bar{3}m$	Cu	0.5800	. . .	. . .	. . .
γ_{Cs}	25	>4.27	?	. . .	. . .	. . .	. . .	. . .	. . .
Cu	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.36146	. . .	. . .	. . .
α'Dy	< -187	atm	*oC*4	*Cmcm*	α'Dy	0.3595	0.6184	0.5678	. . .
αDy	25	atm	*hP*2	$P6_3/mmc$	Mg	0.35915	. . .	0.56501	1.5732
β_{Dy}	>1381	atm	*cI*2	$Im\bar{3}m$	W	(0.398)	. . .	. . .	. . .

γDy	25	>7.5	*hR*3	$R\bar{3}m$	$CdCl_2$	0.3436	. . .	2.483	4.5 × 1.606
Er	25	atm	*hP*2	$P6_3/mmc$	Mg	0.35592	. . .	0.55850	1.5692
αEs	25	atm	*hP*4	$P6_3/mmc$	αLa	?	. . .	. . .	. . .
βEs	?	atm	*cF*4	$Fm\bar{3}m$	Cu	?	. . .	. . .	. . .
Eu	25	atm	*cI*2	$Im\bar{3}m$	W	0.45827	. . .	. . .	. . .
αF	< -227.60	atm	*mC*8	$C2/c$	αF	0.550	0.338	0.728	β= 102.17°
βF	< -219.67	atm	*cP*16	$Pm\bar{3}n$	γO	0.667	. . .	. . .	. . .
αFe	25	atm	*cI*2	$Im\bar{3}m$	W	0.28665	. . .	. . .	. . .
γFe	>912	atm	*cF*4	$Fm\bar{3}m$	Cu	0.36467	. . .	. . .	. . .
δFe	>1394	atm	*cI*2	$Im\bar{3}m$	W	0.29315	. . .	. . .	. . .
εFe	25	>13	*hP*2	$P6_3/mmc$	Mg	0.2468	. . .	0.396	1.603
αGa	25	atm	*oC*8	$Cmca$	αGa	0.45186	0.76570	0.45258	. . .
βGa	25	>1.2	*tI*2	$I4/mmm$	In	0.2808	. . .	0.4458	1.588
γGa	-53	>3.0	*oC*40	$Cmcm$	γGa	1.0593	1.3523	0.5203	. . .
αGd	25	atm	*hP*2	$P6_3/mmc$	Mg	0.36336	. . .	0.57810	1.5910
βGd	>1235	atm	*cI*2	$Im\bar{3}m$	W	0.406	. . .	. . .	. . .
γGd	25	>3.0	*hR*3	$R\bar{3}m$	αSm	0.361	. . .	2.603	4.5 × 1.60
αGe	25	atm	*cF*8	$Fd\bar{3}m$	C(diamond)	0.56574	. . .	. . .	. . .
βGe	25	>12	*tI*4	$I4_1/amd$	βSn	0.4884	. . .	0.2692	0.551

γ_{Ge}	25	>12 → atm	*tP*12	$P4_12_12$	γ_{Ge}	0.593	. . .	0.698	1.18
δ_{Ge}	LT	>12	*cI*16	$Im\bar{3}m$	γ_{Si}	0.692	. . .	. . .	. . .
αH	<-271.9	atm	*cF*4	$Fm\bar{3}m$	Cu	0.5338	. . .	. . .	. . .
β_{H_3}	<-259.34	atm	*hP*2	$P6_3/mmc$	Mg	0.3776	. . .	0.6162	1.632
He$_4$	-269.67	0.163	*hP*2	$P6_3/mmc$	Mg	0.3501	. . .	0.5721	1.634
He	-269.2	0.129	*hP*2	$P6_3/mmc$	Mg	0.3470	. . .	0.5540	1.597
αHf	25	atm	*hP*2	$P6_3/mmc$	Mg	0.31946	. . .	0.50510	1.5811
β_{Hf}	>1743	atm	*cI*2	$Im\bar{3}m$	W	0.3610	. . .	. . .	. . .
αHg	<-38.836	atm	*hR*1	$R\bar{3}m$	αHg	0.3005	. . .	. . .	α= 170.35°
β_{Hg}	<-194	HP	*tI*2	*I*4/*mmm*	β_{Hg}	0.3995	. . .	0.2825	0.707
αHo	25	atm	*hP*2	$P6_3/mmc$	Mg	0.35778	. . .	0.56178	1.5702
β_{Ho}	25	>7.5	*hR*3	$R\bar{3}m$	αSm	0.334	. . .	2.45	4.5 × 1.63
I	25	atm	*oC*8	*Cmca*	I_2	0.72697	0.47903	0.97942	. . .
In	25	atm	*tI*2	*I*4/*mmm*	In	0.3253	. . .	0.49470	1.5210
Ir	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.38392	. . .	. . .	. . .
K	25	atm	*cI*2	$Im\bar{3}m$	W	0.5321	. . .	. . .	. . .
Kr	<-157.385	atm	*cF*4	$Fm\bar{3}m$	Cu	0.5810	. . .	. . .	. . .
αLa	25	atm	*hP*4	$P6_3/mmc$	αLa	0.37740	. . .	1.2171	2 × 1.6125
β_{La}	>310	atm	*cF*4	$Fm\bar{3}m$	Cu	0.5303	. . .	. . .	. . .

γLa	>865	atm	*cI*2	$Im\bar{3}m$	W	0.426	. . .	. . .	. . .
β'La	25	>2.0	*cF*4	$Fm\bar{3}m$	Cu	0.517	. . .	. . .	. . .
αLi	<-193	atm	*hP*2	$P6_3/mmc$	Mg	0.3111	. . .	0.5093	1.637
βLi	25	atm	*cI*2	$Im\bar{3}m$	W	0.35093	. . .	. . .	. . .
Lu	25	atm	*hP*2	$P6_3/mmc$	Mg	0.35052	. . .	0.55494	1.5832
Mg	25	atm	*hP*2	$P6_3/mmc$	Mg	0.32094	. . .	0.52107	1.6236
αMn	25	atm	*cI*58	$I\bar{4}3m$	αMn	0.89126	. . .	. . .	. . .
βMn	>727	atm	*cP*20	$P4_132$	βMn	0.63152	. . .	. . .	. . .
γMn	>1100	atm	*cF*4	$Fm\bar{3}m$	Cu	0.3860	. . .	. . .	. . .
δMn	>1138	atm	*cI*2	$Im\bar{3}m$	W	0.3080	. . .	. . .	. . .
Mo	25	atm	*cI*2	$Im\bar{3}m$	W	0.31470	. . .	. . .	. . .
αN	<237.54	atm	*cP*8	*Pa*3	αN	0.5661	. . .	. . .	. . .
βN	<210.004	atm	*hP*4	$P6_3/mmc$	βN	0.4050	. . .	0.6604	1.631
γN	<-253	>3.3	*tP*4	$P4_2/mnm$	γN	0.3957	. . .	0.5109	1.291
αNa	<-253	atm	*hP*2	$P6_3/mmc$	Mg	0.3767	. . .	0.6154	1.634
βNa	25	atm	*cI*2	$Im\bar{3}m$	W	0.42906	. . .	. . .	. . .
Nb	25	atm	*cI*2	$Im\bar{3}m$	W	0.33004	. . .	. . .	. . .
αNd	25	atm	*hP*4	$P6_3/mmc$	αLa	0.36582	. . .	1.17966	2 × 1.6124
βNd	>863	atm	*cI*2	$Im\bar{3}m$	W	0.413	. . .	. . .	. . .

γNd	25	>5.0	*cF*4	$Fm\bar{3}m$	Cu	0.480	. . .	. . .	. . .
Ne	<-248.587	atm	*cF*4	$Fm\bar{3}m$	Cu	0.480	. . .	. . .	. . .
Ni	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.4462	. . .	. . .	. . .
αNp	25	atm	*oP*8	*Pnma*	αNp	0.6663	0.4723	0.4887	. . .
βNp	>280	atm	*tP*4	$P42_12$	βNp	0.4883	. . .	0.3389	0.694
γNp	>576	atm	*cI*2	$Im\bar{3}m$	W	0.352	. . .	. . .	. . .
αO	<-249.283	atm	*mC*4	*C*2*m*	αO	0.5403	0.3429	0.5086	β = 132.53°
βO	<229.349	atm	*hR*2	$R\bar{3}m$	βO	0.4210	. . .	. . .	α = 46.27°
γO	<218.789	atm	cP16	$Pm\bar{3}/n$	γO	0.683	. . .	. . .	. . .
Os	25	atm	*hP*2	$P6_3/mmc$	Mg	0.27341	. . .	0.43198	1.5800
αP(white)	25	atm	c**	. . .	P(white)	0.718	. . .	. . .	. . .
P(black)	25	atm	*oC*8	*Cmca*	P(black)	0.33136	1.0478	0.43763	. . .
αPa	25	atm	*tI*2	*I*4/*mmm*	αPa	0.3921	. . .	0.3235	0.825
βPa	>1170	atm	*cI*2	$Im\bar{3}m$	W	0.381	. . .	. . .	. . .
αPb	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.49502	. . .	. . .	. . .
βPb	25	>10.3	*hP*2	$P6_3/mmc$	Mg	0.3265	. . .	0.5387	1.650
Pd	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.38903	. . .	. . .	. . .
αPm	25	atm	*hP*4	$P6_3/mmc$	αLa	0.365	. . .	1.165	2 × 1.60
βPm	>890	atm	*cI*2	$Im\bar{3}m$	W	?	. . .	. . .	. . .

αPo	25	atm	*cP*1	$Pm\bar{3}m$	αPo	0.3366	. . .	. . .	. . .
β_{Po}	>54	atm	*hR*1	$R\bar{3}m$	β_{Po}	0.3373	. . .	. . .	α= 98.08°
αPr	25	atm	*hP*4	$P6_3/mmc$	αLa	0.36721	. . .	1.18326	2 × 1.6111
β_{Pr}	>795	atm	*cI*2	$Im\bar{3}m$	W	0.413	. . .	. . .	. . .
γ_{Pr}	25	>4.0	*cF*4	$Fm\bar{3}m$	Cu	0.488	. . .	. . .	. . .
Pt	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.39236	. . .	. . .	. . .
αPu	25	atm	*mP*16	$P2_1/m$	αPu	0.6183	0.4822	1.0963	β= 101.97°
β_{Pu}	>125	atm	*mC*34	$C2/m$	β_{Pu}	0.9284	1.0463	0.7859	β= 92.13°
γ_{Pu}	>215	atm	*oF*8	*Fddd*	γ_{Pu}	0.31587	0.57682	1.0162	. . .
δPu	>320	atm	*cF*4	$Fm\bar{3}m$	Cu	0.46371	. . .	. . .	. . .
δ'Pu	>463	atm	*tI*2	*I*4/*mmm*	In	0.33261	. . .	0.44630	1.3418
εPu	>483	atm	*cI*2	$Im\bar{3}m$	W	0.36343	. . .	. . .	. . .
Ra	25	atm	*cI*2	$Im\bar{3}m$	W	0.5148	. . .	. . .	. . .
αRb	25	atm	*cI*2	$Im\bar{3}m$	W	0.5705	. . .	. . .	. . .
β_{Rb}	25	>1.08	?	. . .	. . .	. . .	. . .	. . .	. . .
γ_{Rb}	25	>2.05	?	. . .	. . .	. . .	. . .	. . .	. . .
Re	25	atm	*hP*2	$P6_3/mmc$	Mg	0.27609	. . .	0.4458	1.6145
Rh	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.38032	. . .	. . .	. . .
Ru	25	atm	*hP*2	$P6_3/mmc$	Mg	0.27058	. . .	0.42816	1.5824

αS	25	atm	*oF*128	*Fddd*	αS	1.0464	1.28660	2.44860	. . .
β_{S}	>95.5	atm	*mP*64	$P2_1/c$	β_{S}	1.102	1.096	1.090	β = 96.7°
αSb	25	atm	*hR*2	$R\bar{3}m$	αAs	0.45067	. . .	. . .	α = 57.11°
β_{Sb}	25	>5.0	*cP*1	$Pm\bar{3}/m$	αPo	0.2992	. . .	. . .	. . .
γ_{Sb}	25	>7.5	*hP*2	$P6_3/mmc$	Mg	0.3376	. . .	0.5341	1.582
δSb	25	>14.0	*mP*3	?	. . .	0.556	0.404	0.422	β = 86.0°
αSc	25	atm	*hP*2	$P6_3/mmc$	Mg	0.33088	. . .	0.52680	1.5921
β_{Sc}	>1337	atm	*cI*2	$Im\bar{3}m$	W	0.373	. . .	. . .	. . .
γ_{Se}	25	atm	*hP*3	$P3_12_1$	γ_{Se}	0.43659	. . .	0.49537	1.1346
αSi	25	atm	*cF*8	$Fd\bar{3}m$	C(diamond)	0.54306	. . .	. . .	. . .
β_{Si}	25	>9.5	*tI*4	$I4_1/amd$	β_{Sn}	0.4686	. . .	0.2585	0.552
γ_{Si}	25	>16.0	*cI*16	$Im\bar{3}m$	γ_{Si}	0.6636	. . .	. . .	. . .
δSi	25	>16 → atm	*hP*4	$P6_3/mmc$	αLa	0.380	. . .	0.628	1.653
αSm	25	atm	*hR*3	R_3m	αSm	0.36290	. . .	2.6207	4.5 × 1.6048
β_{Sm}	>734	atm	*hP*2	$P6_3/mmc$	Mg	0.36630	. . .	0.58448	1.5956
γ_{Sm}	>922	atm	*cI*2	$Im\bar{3}m$	W	?	. . .	. . .	. . .
δSm	25	>4.0	*hP*4	$P6_3/mmc$	αLa	0.3618	. . .	1.166	2 × 1.611
αSn	<13	atm	*cF*8	$Fd\bar{3}\mathrm{m}$	C(diamond)	0.64892	. . .	. . .	. . .
β_{Sn}	25	atm	*tI*4	$I4_1/amd$	β_{Sn}	0.58318	. . .	0.31818	0.5456

γ_{Sn}	25	>9.0	*tI*2	?	γ_{Sn}	0.370	. . .	0.337	0.91
αSr	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.6084	. . .	. . .	. . .
β_{Sr}	>547	atm	*cI*2	$Im\bar{3}m$	W	0.487	. . .	. . .	. . .
β'_{Sr}	25	>3.5	*cI*2	$Im\bar{3}m$	W	0.4437	. . .	. . .	. . .
Ta	25	atm	*cI*2	$Im\bar{3}m$	W	0.33030	. . .	. . .	. . .
αTb	<-53	atm	*oC*4	$Cmcm$	α'Dy	0.3605	0.6244	0.5706	. . .
α' Tb	25	atm	*hP*2	$P6_3/mmc$	Mg	0.36055	. . .	0.56966	1.5800
β_{Tb}	>1289	atm	*cI*2	$Im\bar{3}m$	W	(0.402)	. . .	. . .	. . .
γ_{Tb}	25	>6.0	*hR*3	$R\bar{3}m$	αSm	0.341	. . .	2.45	4.5 × 1.60
Tc	25	atm	*hP*2	$P6_3/mmc$	Mg	0.2738	. . .	0.4393	1.604
αTe	25	atm	*hP*3	$P3_121$	γ_{Se}	0.44566	. . .	0.59264	1.3298
β_{Te}	25	>2.0	*hR*2	$R\bar{3}m$	αAs	0.469	. . .	. . .	α= 53.30°
γ_{Te}	25	>7.0	*hR*1	$R\bar{3}m$	β_{Po}	0.3002	. . .	. . .	α= 103.3°
αTh	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.50842	. . .	. . .	. . .
β_{Th}	>1360	atm	*cI*2	$Im\bar{3}m$	W	0.411	. . .	. . .	. . .
αTi	25	atm	*hP*2	$P6_3/mmc$	Mg	0.29506	. . .	0.46835	1.5873
β_{Ti}	>882	atm	*cI*2	$Im\bar{3}m$	W	0.411	. . .	. . .	. . .
ωTi	25	HP → atm	*hP*3	$P6/mmm$	ωTi	0.4625	. . .	0.2813	0.6082
αTl	25	atm	*hP*2	$P6_3/mmc$	Mg	0.34566	. . .	0.55248	1.5983

β_{Tl}	>230	atm	*cI*2	$Im\bar{3}m$	W	0.3879	. . .	. . .	. . .
γ_{Tl}	25	HP	*cF*4	$Fm\bar{3}m$	Cu	?	. . .	. . .	. . .
Tm	25	atm	*hP*2	$P6_3/mmc$	Mg	0.35375	. . .	0.55540	1.5700
αU	25	atm	*oC*4	*Cmcm*	αU	0.28537	0.58695	0.49548	. . .
β_{U}	>668	atm	*tP*30	$P4_2/mnm$	β_{U}	1.0759	. . .	0.5656	0.526
γ_{U}	>776	atm	*cI*2	$Im\bar{3}m$	W	0.3524	. . .	. . .	. . .
V	25	atm	*cI*2	$Im\bar{3}m$	W	0.30240	. . .	. . .	. . .
W	25	atm	*cI*2	$Im\bar{3}m$	W	0.31652	. . .	. . .	. . .
Xe	<-111.758	atm	*cF*4	$Fm\bar{3}m$	Cu	0.6350	. . .	. . .	. . .
αY	25	atm	*hP*2	$P6_3/mmc$	Mg	0.36482	. . .	0.57318	1.5711
β_{Y}	>1478	atm	*cI*2	$Im\bar{3}m$	W	(0.407)	. . .	. . .	. . .
αYb	<-3	atm	*hP*2	$P6_3/mmc$	Mg	0.38799	. . .	0.63859	1.6459
β_{Yb}	25	atm	*cF*4	$Fm\bar{3}m$	Cu	0.54848	. . .	. . .	. . .
γ_{Yb}	>795	atm	*cI*2	$Im\bar{3}m$	W	0.444	. . .	. . .	. . .
Zn	25	atm	*hP*2	$P6_3/mmc$	Mg	0.26650	. . .	0.49470	1.8563
αZr	25	atm	*hP*2	$P6_3/mmc$	Mg	0.32316	. . .	0.51475	1.5929
β_{Zr}	>863	atm	*cI*2	$Im\bar{3}m$	W	0.36090	. . .	. . .	. . .
ωZr	25	HP → atm	*hP*2	*P*6/*mmm*	ωTi	0.5036	. . .	0.3109	0.617

Note: Values in parentheses are estimated.

Source: *Alloy Phase Diagrams,* Vol 3, *ASM Handbook,* ASM International, 1992, p 14-10 to 14-12

(a) HP, high pressure.

(b) The lattice parameter of the unit cells are considered to be accurate ±2 in the last reported digit.

An important source of information on crystal structures for many years was *Structure Reports* (*Strukturbericht* in German). In this publication, crystal structures were classified by a designation consisting of a capital letter (*A* for elements, *B* for AB-type phases, *C* for AB_2-type phases, *D* for other binary phases, *E* for ternary phases, and *L* for superlattices), followed a number consecutively assigned (within each group) at the time the type was reported. To further distinguish among crystal types, inferior letters and numbers, as well as prime marks, were added to some designations. Because the Strukturbericht designation cannot be conveniently and systematically expanded to cover the large variety of crystal structures currently being encountered, the system is falling into disuse. Relations among Strukturbericht designations and Pearson symbols, space groups, structure prototypes can be found in the Appendix to Volume 3, *Alloy Phase Diagrams,* of the *ASM Handbook.*

Solid-Solution Mechanisms. There are only two mechanisms by which a metal crystal can dissolve atoms of a different element. If the atoms of the solute element are sufficiently smaller than the atoms comprising the solvent crystal, the solute atoms can fit into the spaces between the larger atoms to form an *interstitial solid solution* (see Fig. 6a). The only solute atoms small enough to fit into the interstices of metal crystals, however, are hydrogen, nitrogen, carbon, and boron. (The other small-diameter atoms, such as oxygen, tend to form compounds with metals rather than dissolve in them.) The rest of the elements dissolve in solid metals by replacing a solvent atom at a lattice point to form a *substitutional solid solution* (see Fig. 6b). When both small and large solute atoms are present, the solid solution can be both interstitial and substitutional. The addition of foreign atoms by either mechanism results in distortion of the crystal lattice and an increase in its internal energy. This distortion energy causes some hardening and strengthening of the alloy called *solution hardening.* The solvent phase becomes saturated with the solute atoms and reaches its limit of homogeneity when the distortion energy reaches a critical value determined by the thermodynamics of the system.

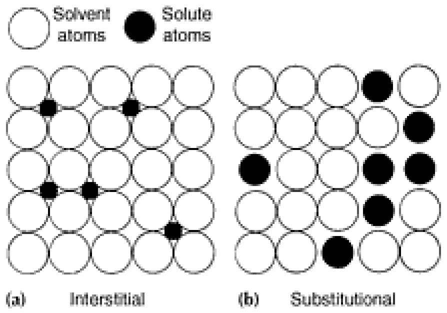


Fig. 6 Solid-solution mechanisms. (a) Interstitial. (b) Substitutional

Ordered Solutions. As mentioned earlier, some alloy solutions in the ordered state have periodic structures having unit cells many times larger than in the disordered state, the long period being either along one axis, as in Fig. 7, or along two axes, as in Fig. 8. The length of a superperiod formed by *long-period ordering* depends on the alloy system and the composition within the system. Figure 7 shows an AuCu II structure having a one-dimensional long-range *superlattice,* with boundaries between the *antiphase domains* at intervals of five unit cells of the disordered state. It is orthorhombic when ordered, and face-centered cubic when disordered. Figure 8 shows a two-dimensional long-period superlattice as in certain AB_3 alloys (Cu-Pd, Au-Zn, Au-Mn), having antiphase boundaries spaced at intervals M_1 and M_2 and unit-cell dimensions *a, b,* and *c,* in the ordered state. This superlattice is orthorhombic when ordered, and face-centered cubic when disordered.

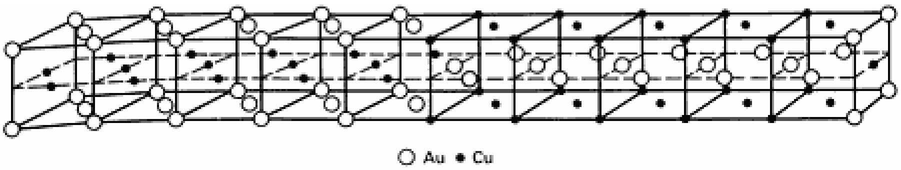


Fig. 7 AuCu II structure; a one-dimensional, long-period superlattice, having antiphase boundaries spaced at intervals of five unit cells of the disordered state

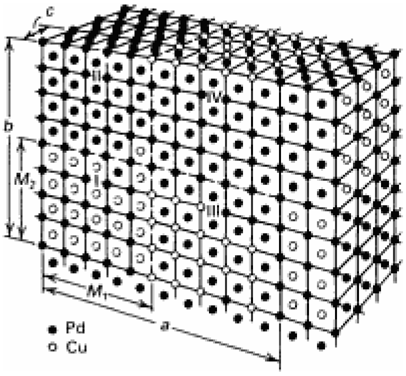


Fig. 8 Two-dimensional, long-period superlattice, having antiphase boundaries spaced at intervals M_1 and M_2 and unit-cell dimensions *a, b,* and *c* in the ordered state. The palladium atom has different positions in the small cubes in domains I, II, III, and IV.

Crystal Defects and Plastic Flow

Crystal defects are important features in all real crystals. Some of the most significant defects are described below.

Point defects include vacant atom positions that are occupied in perfect crystals. These vacancies increase in number as temperature is increased, and by jumping about from one lattice site to another they cause diffusion.

Interstitial B atoms are those located between the A atoms of the normal perfect-crystal array; thus, the carbon atoms in bcc ferrite are interstitials in that they fit between the iron atoms of its bcc structure, which is similar to the *cI*2 type illustrated in Fig. 4. Substitutional B atoms are located at atom positions formerly occupied by A atoms in a normal, perfect-crystal array. A B atom in either substitutional or interstitial solid solution is another common form of point defect.

There are also many close pairs and clusters of point defects, such as divacancies, trivacancies, and interstitial-vacancy pairs.

Line Defects. *Dislocations* are *line defects* that exist in all real crystals. An *edge dislocation,* which is the edge of an incomplete plane of atoms within a crystal, is represented in cross section in Fig. 9. In this illustration, the incomplete plane extends part way through the crystal from the top down, and the edge dislocation (which is indicated by the standard symbol (⊥) is its lower edge.

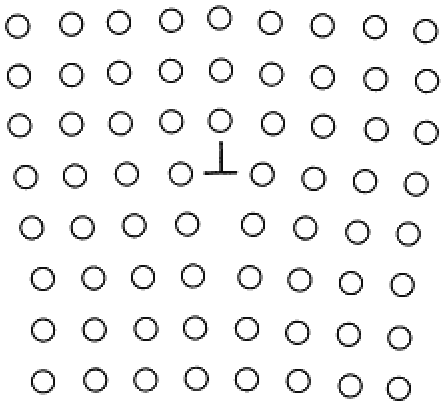
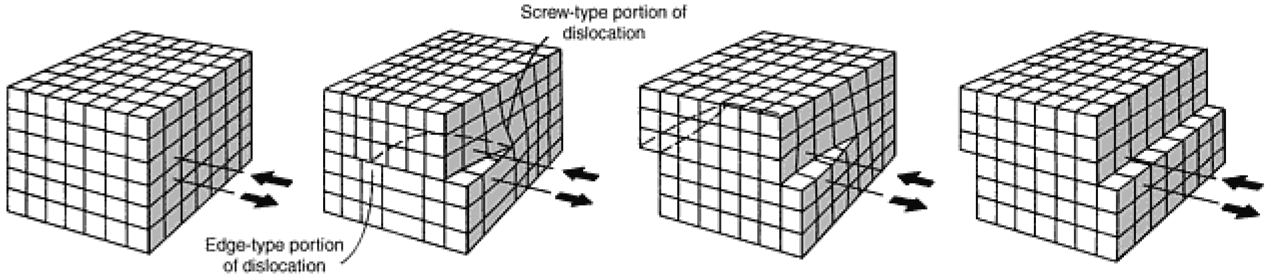


Fig. 9 A section through an edge dislocation, which is perpendicular to the plane of the illustration and is indicated by the symbol ⊥.

If forces, as indicated by the arrows in Fig. 10, are applied to a crystal, such as the perfect crystal shown in Fig. 10(a), one part of the crystal will slip. The edge of the slipped region, shown as a dashed line in Fig. 10(b), is a dislocation. The portion of the line at the left near the front of the crystal and perpendicular to the arrows, in Fig. 10(b), is an edge dislocation, because the displacement involved is perpendicular to the dislocation.


Screw-type portion of dislocation
Edge-type portion of dislocation

(a) Crystal before displacement
(b) Crystal after some displacement
(c) Complete displacement across part of crystal
(d) Complete displacement across entire crystal

Fig. 10 Four stages of slip deformation by formation and movement of a dislocation (dashed line) through a crystal

The *slip deformation* in Fig. 10(b) has also formed another type of dislocation. The part of the slipped region near the right side, where the displacement is parallel to the dislocation, is called a *screw dislocation.* In this part, the crystal no longer is made of parallel planes of atoms, but instead consists of a single plane in the form of a helical ramp (screw).

As the slipped region spreads across the slip plane, the edge-type portion of the dislocation moves out of the crystal leaving the screw-type portion still embedded, as shown in Fig. 10(c). When all of the dislocation finally emerges from the crystal, the crystal is again perfect, but with the upper part displaced one unit cell from the lower part, as shown in Fig. 10(d). Thus, Fig. 10 illustrates the mechanism of *plastic flow* by the slip process, which is actually flow by dislocation movement.

The displacement that occurs when a dislocation passes a point is described by a vector, known as the Burgers vector (**b**). The direction of the vector with respect to the dislocation line and the length of the vector with respect to the identity distance in the direction of the vector are the fundamental characteristics of a dislocation. The perfection of a crystal lattice is restored after the passage of a dislocation, as indicated in Fig. 10(d), provided no additional defects are generated in the process.

Each dislocation that remains in a crystal is the source of local stresses. The nature of these microstresses is indicated by the arrows in Fig. 11, which presents (qualitatively) the stresses acting on small volumes at different positions around the dislocation at the lower edge of the incomplete plane of atoms. Interstitial atoms usually cluster in regions where tensile stresses make more room for them, as in the lower central part of Fig. 11.

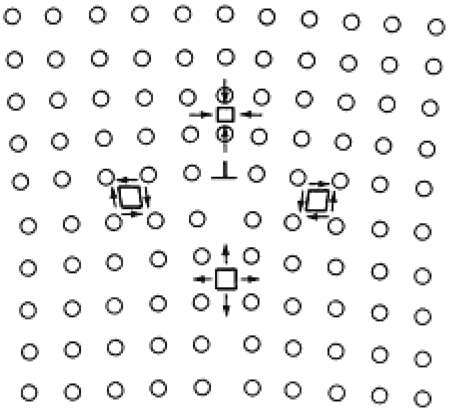


Fig. 11 Crystal containing an edge dislocation, indicating qualitatively the stress (shown by the direction of the arrows) at four positions around the dislocation

Individual crystal grains, which have different lattice orientations, are separated by large-angle boundaries (*grain boundaries*). In addition, the individual grains are separated by small-angle boundaries (*subboundaries*) into *subgrains* that differ very little in orientation. These subboundaries may be considered as arrays of dislocations; *tilt boundaries* are arrays of edge dislocations, *twist boundaries* are arrays of screw dislocations. A tilt boundary is represented in Fig. 12 by the series of edge dislocations in a vertical row. Compared with large-angle boundaries, small-angle boundaries are less severe defects, obstruct plastic flow less, and are less effective as regions for chemical attack and segregation of alloying constituents. In general, mixed types of grain-boundary defects are common. All grain boundaries are sinks into which vacancies and dislocations can disappear and may also serve as sources of these defects; they are important factors in creep deformation.

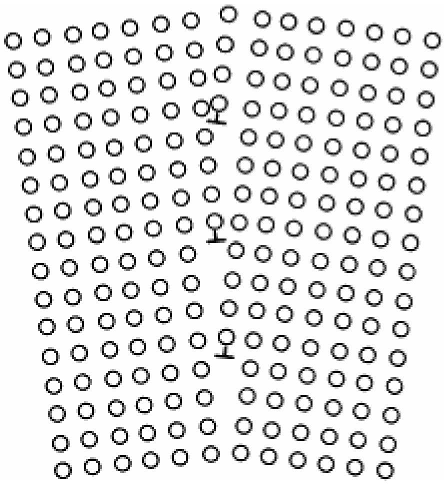


Fig. 12 Small-angle boundary (subboundary) of the tilt type, which consists of a vertical array of edge dislocations

Stacking faults are two-dimensional defects that are planes where there is an error in the normal sequence of stacking of atom layers. Stacking faults may be formed during the growth of a crystal. They may also result from motion of *partial dislocations.* Contrary to a *full dislocation,* which produces a displacement of a full distance between the lattice points, a partial dislocation produces a movement that is less than a full distance.

Twins are portions of a crystal that have certain specific orientations with respect to each other. The twin relationship may be such that the lattice of one part is the mirror image of that of the other, or one part may be related to the other by a certain rotation about a certain crystallographic axis. *Growth twins* may occur frequently during crystallization from the liquid or the vapor state, by growth during annealing (by recrystallization or by grain-growth processes), or by the movement between solid phases such as during phase transformation. Plastic deformation by shear may produce *deformation twins (mechanical twins).* Twin boundaries generally are very flat, appearing as straight lines in micrographs, and are two-dimensional defects of lower energy than large-angle grain boundaries. Twin boundaries are, therefore, less effective as sources and sinks of other defects and are less active in deformation and corrosion than are ordinary grain boundaries.

Cold Work. Plastic deformation of a metal at a temperature at which annealing does not rapidly take place is called *cold work*, that temperature depending mainly on the metal in question. As the amount of cold work builds up, the distortion caused in the internal structure of the metal makes further plastic deformation more difficult, and the strength and hardness of the metal increases.

Alloy Phase Diagrams and Microstructure

Hugh Baker, Consulting Editor, ASM International

Introduction

ALLOY PHASE DIAGRAMS are useful to metallurgists, materials engineers, and materials scientists in four major areas: (1) development of new alloys for specific applications, (2) fabrication of these alloys into useful configurations, (3) design and control of heat treatment procedures for specific alloys that will produce the required mechanical, physical, and chemical properties, and (4) solving problems that arise with specific alloys in their performance in commercial applications, thus improving product predictability. In all these areas, the use of phase diagrams allows research, development, and production to be done more efficiently and cost effectively.

In the area of alloy development, phase diagrams have proved invaluable for tailoring existing alloys to avoid overdesign in current applications, designing improved alloys for existing and new applications, designing special alloys for special applications, and developing alternative alloys or alloys with substitute alloying elements to replace those containing scarce, expensive, hazardous, or "critical" alloying elements. Application of alloy phase diagrams in processing includes their use to select proper parameters for working ingots, blooms, and billets, finding causes and cures for microporosity and cracks in castings and welds, controlling solution heat treating to prevent damage caused by incipient melting, and developing new processing technology.

In the area of performance, phase diagrams give an indication of which phases are thermodynamically stable in an alloy and can be expected to be present over a long time when the part is subjected to a particular temperature (e.g., in an automotive exhaust system). Phase diagrams also are consulted when attacking service problems such as pitting and intergranular corrosion, hydrogen damage, and hot corrosion.

In a majority of the more widely used commercial alloys, the allowable composition range encompasses only a small portion of the relevant phase diagram. The nonequilibrium conditions that are usually encountered in practice, however, necessitate the knowledge of a much greater portion of the diagram. Therefore, a thorough understanding of alloy phase diagrams in general and their practical use will prove to be of great help to a metallurgist expected to solve problems in any of the areas mentioned above.

Common Terms

Phases. All materials exist in gaseous, liquid, or solid form (usually referred to as a "phase"), depending on the conditions of state. *State variables* include composition, temperature, pressure, magnetic field, electrostatic field, gravitational field, and so forth. The term "phase" refers to that region of space occupied by a physically homogeneous material. However, there are two uses of the term: the strict sense normally used by physical scientists and the somewhat less strict sense normally used by materials engineers. In the strictest sense, homogeneous means that the physical properties throughout the region of space occupied by the phase are absolutely identical, and any change in condition of state, no matter how small, will result in a different phase. For example, a sample of solid metal with an apparently homogeneous appearance is not truly a single-phase material because the pressure condition varies in the sample due to its own weight in the gravitational field.

In a phase diagram, however, each single-phase field (phase fields are discussed in a later section) is usually given a single label, and engineers often find it convenient to use this label to refer to all the materials lying within the field, regardless of how much the physical properties of the materials continuously change from one part of the field to another. This means that in engineering practice, the distinction between the terms "phase" and "phase field" is seldom made, and all materials having the same phase name are referred to as the same phase.

Equilibrium. There are three types of equilibria: stable, metastable, and unstable. These three are illustrated in a mechanical sense in Fig. 1. Stable equilibrium exists when the object is in its lowest energy condition; metastable equilibrium exists when additional energy must be introduced before the object can reach true stability; unstable equilibrium exists when no additional energy is needed before reaching metastability or stability. Although true stable equilibrium conditions seldom exist in metal objects, the study of equilibrium systems are extremely valuable, because it constitutes a limiting condition from which actual conditions can be estimated.

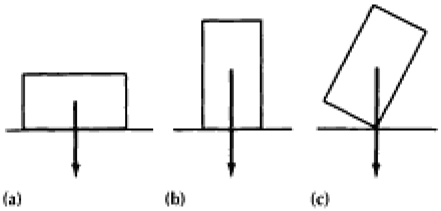


Fig. 1 Mechanical equilibria. (a) Stable. (b) Metastable. (c) Unstable

Polymorphism. The structure of solid elements and compounds under stable equilibrium conditions is crystalline, and the crystal structure of each is unique. Some elements and compounds, however, are *polymorphic* (multishaped), that is, their structure transforms from one crystal structure to another with changes in temperature and pressure, each unique structure constituting a distinctively separate phase. The term *allotropy* (existing in another form) is usually used to describe polymorphic changes in chemical elements (see the table contained in Appendix 2 to this article).

Metastable Phases. Under some conditions, metastable crystal structures can form instead of stable structures. Rapid freezing is a common method of producing metastable structures, but some (such as Fe_3C, or "cementite") are produced at moderately slow cooling rates. With extremely rapid freezing, even thermodynamically unstable structures (such as amorphous metallic "glasses") can be produced.

Systems. A physical *system* consists of a substance (or a group of substances) that is isolated from its surroundings, a concept used to facilitate study of the effects of conditions of state. By "isolated," it is meant that there is no interchange of mass with its surroundings. The substances in alloy systems, for example, might be two metals such as copper and zinc; a metal and a nonmetal such as iron and carbon; a metal and an intermetallic compound such as iron and cementite; or several metals such as aluminum, magnesium, and manganese. These substances constitute the *components* comprising the system and should not be confused with the various phases found within the system. A system, however, also can consist of a single component, such as an element or compound.

Phase Diagrams. In order to record and visualize the results of studying the effects of state variables on a system, diagrams were devised to show the relationships between the various phases that appear within the system under equilibrium conditions. As such, the diagrams are variously called *constitutional diagrams, equilibrium diagrams*, or *phase diagrams.* A single-component phase diagram can be simply a one- or two-dimensional plot showing the phase changes in the substance as temperature and/or pressure change. Most diagrams, however, are two- or three-dimensional plots describing the phase relationships in systems made up of two or more components, and these usually contain fields (areas) consisting of mixed-phase fields, as well as single-phase fields. The plotting schemes in common use are described in greater detail in subsequent sections of this article.

System Components. Phase diagrams and the systems they describe are often classified and named for the number (in Latin) of components in the system, as shown below:

No. of components	**Name of system or diagram**
One	Unary
Two	Binary
Three	Ternary
Four	Quaternary
Five	Quinary
Six	Sexinary
Seven	Septenary
Eight	Octanary
Nine	Nonary
Ten	Decinary

The phase rule, first announced by J. Willard Gibbs in 1876, relates the physical state of a mixture to the number of constituents in the system and to its conditions. It was also Gibbs that first called the homogeneous regions in a system by the term "phases." When pressure and temperature are the state variables, the rule can be written as follows:

$$f = c - p + 2$$

where f is the number of independent variables (called *degrees of freedom*), c is the number of components, and p is the number of stable phases in the system.

Unary Diagrams

Invariant Equilibrium. According to the phase rule, three phases can exist in stable equilibrium only at a single point on a unary diagram ($f = 1 - 3 + 2 = 0$). This limitation is illustrated as point 0 in the hypothetical unary pressure-temperature (*PT*) diagram shown in Fig. 2. In this diagram, the three states (or phases)--solid, liquid, and gas--are represented by the three correspondingly labeled fields. Stable equilibrium between any two phases occurs along their mutual boundary, and *invariant equilibrium* among all three phases occurs at the so-called *triple point,* 0, where the three boundaries intersect. This point also is called an *invariant point* because at that location on the diagram, all externally controllable factors are fixed (no degrees of freedom). At this point, all three states (phases) are in equilibrium, but any changes in pressure and/or temperature will cause one or two of the states (phases) to disappear.

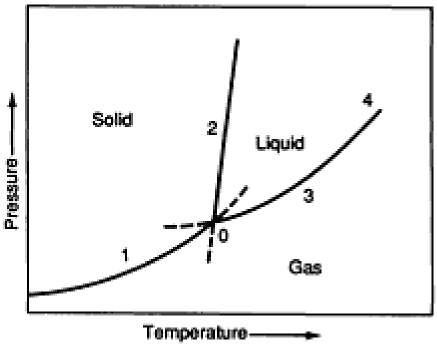


Fig. 2 Pressure-temperature phase diagram

Univariant Equilibrium. The phase rule says that stable equilibrium between two phases in a unary system allows one degree of freedom (f = 1 - 2 + 2). This condition, which is called *univariant equilibrium* or *monovariant equilibrium,* is illustrated as lines 1, 2, and 3 that separate the single-phase fields in Fig. 2. Either pressure or temperature may be freely selected, but not both. Once a pressure is selected, there is only one temperature that will satisfy equilibrium conditions, and conversely. The three curves that issue from the triple point are called *triple curves:* line 1 representing reaction between the solid and the gas phases is the *sublimation curve;* line 2 is the *melting curve;* and line 3 is the *vaporization curve.* The vaporization curve ends at point 4, called a *critical point,* where the physical distinction between the liquid and gas phases disappears.

Bivariant Equilibrium. If both the pressure and temperature in a unary system are freely and arbitrarily selected, the situation corresponds to having two degrees of freedom, and the phase rule says that only one phase can exist in stable equilibrium (p = 1 - 2 + 2). This situation is called *bivariant equilibrium.*

Binary Diagrams

If the system being considered comprises two components, it is necessary to add a composition axis to the *PT* plot, which would require construction of a three-dimensional graph. Most metallurgical problems, however, are concerned only with a fixed pressure of one atmosphere, and the graph reduces to a two-dimensional plot of temperature and composition (*TX*) diagram.

The Gibbs phase rule applies to all states of matter, solid, liquid, and gaseous, but when the effect of pressure is constant, the rule reduces to:

$$f = c - p + 1$$

The stable equilibria for binary systems are summarized as follows:

No. of components	No. of phases	Degrees of freedom	Equilibrium
2	3	0	Invariant
2	2	1	Univariant
2	1	2	Bivariant

Miscible Solids. Many systems are composed of components having the same crystal structure, and the components of some of these systems are completely miscible (completely soluble in each other) in the solid form, thus forming a *continuous solid solution.* When this occurs in a binary system, the phase diagram usually has the general appearance of that shown in Fig. 3. The diagram consists of two single-phase fields separated by a two-phase field. The boundary between the liquid field and the two-phase field in Fig. 3 is called the *liquidus;* that between the two-phase field and the solid field is the *solidus.* In general, a liquidus is the locus of points in a phase diagram representing the temperatures at which alloys of the various compositions of the system begin to freeze on cooling or finish melting on heating; a solidus is the locus of points representing the temperatures at which the various alloys finish freezing on cooling or begin melting on heating. The phases in equilibrium across the two-phase field in Fig. 3 (the liquid and solid solutions) are called *conjugate phases.*

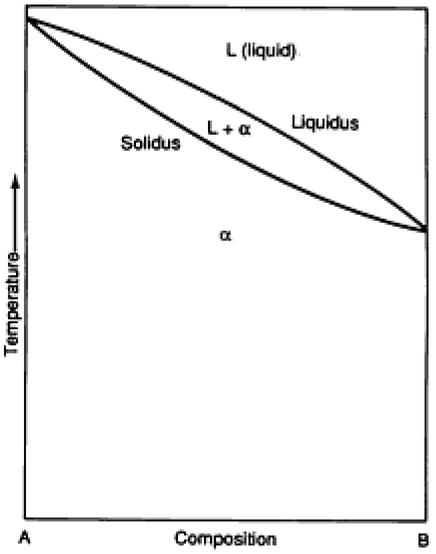


Fig. 3 Binary phase diagram showing miscibility in both the liquid and solid states

If the solidus and liquidus meet tangentially at some point, a maximum or minimum is produced in the two-phase field, splitting it into two portions as shown in Fig. 4. It also is possible to have a gap in miscibility in a single-phase field; this is shown in Fig. 5. Point T_c, above which phases α_1 and α_2 become indistinguishable, is a critical point similar to point 4 in Fig. 2. Lines a-T_c and b-T_c, called *solvus* lines, indicate the limits of solubility of component B in A and A in B, respectively.

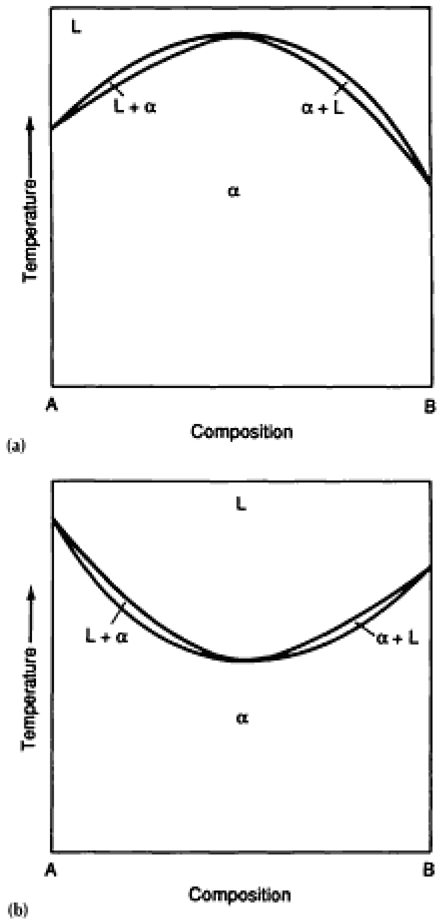

L
L + α
α + L
α
Temperature
A
B
Composition
(a)
L
L + α
α + L
α
Temperature
A
B
Composition
(b)

Fig. 4 Binary phase diagrams with solid-state miscibility where the liquidus shows (a) a maximum and (b) a minimum

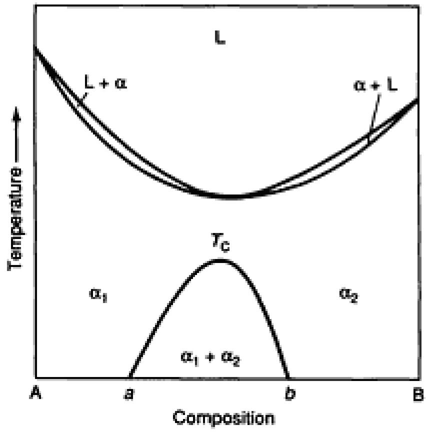

L
L + α
α + L
Temperature
T_C
α_1
α_2
$\alpha_1 + \alpha_2$
A
a
b
B
Composition

Fig. 5 Binary phase diagram with a minimum in the liquidus and a miscibility gap in the solid state

The configuration of these and all other phase diagrams depends on the thermodynamics of the system, as discussed in the section on "Thermodynamics and Phase Diagrams," which appears later in this article.

Eutectic Reactions. If the two-phase field in the solid region of Fig. 5 is expanded so it touches the solidus at some point, as shown in Fig. 6(a), complete miscibility of the components is lost. Instead of a single solid phase, the diagram now shows two separate solid *terminal phases,* which are in three-phase equilibrium with the liquid at point *P*, an invariant point that occurred by coincidence. (Three-phase equilibrium is discussed in the following section.) Then, if this two-phase field in the solid region is even further widened so that the solvus lines no longer touch at the invariant point, the diagram passes through a series of configurations, finally taking on the more familiar shape shown in Fig. 6(b). The three-phase reaction that takes place at the invariant point *E,* where a liquid phase freezes into a mixture of two solid phases, is called a *eutectic* reaction (from the Greek for *easily melted*). The alloy that corresponds to the eutectic composition is called a *eutectic alloy.* An alloy having a composition to the left of the eutectic point is called a *hypoeutectic alloy* (from the Greek word for *less than*); an alloy to right is a *hypereutectic alloy* (meaning *greater than*).

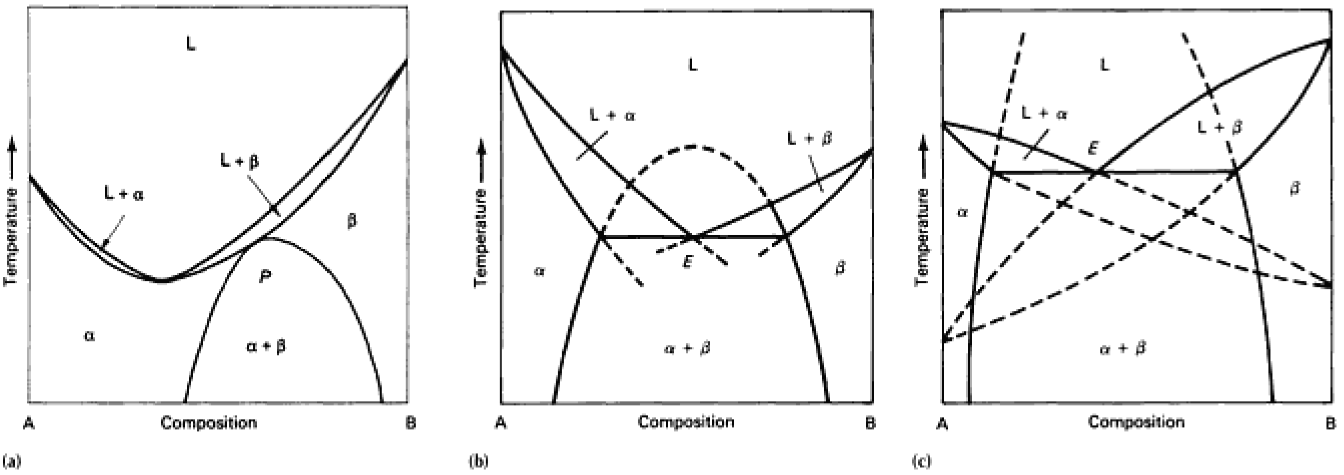


Fig. 6 Binary phase diagrams with invariant points. (a) Hypothetical diagram of the type of shown in Fig. 5, except that the miscibility gap in the solid touches the solidus curve at invariant point *P*; an actual diagram of this type probably does not exist. (b) and (c) Typical eutectic diagrams for (b) components having the same crystal structure, and (c) components having different crystal structures; the eutectic (invariant) points are labeled *E*. The dashed lines in (b) and (c) are metastable extensions of the stable-equilibria lines.

In the eutectic system described above, the two components of the system have the same crystal structure. This, and other factors, allows complete miscibility between them. Eutectic systems, however, also can be formed by two components having different crystal structures. When this occurs, the liquidus and solidus curves (and their extensions into the two-phase field) for each of the terminal phases (see Fig. 6c) resemble those for the situation of complete miscibility between system components shown in Fig. 3.

Three-Phase Equilibrium. Reactions involving three conjugate phases are not limited to the eutectic reaction. For example, a single solid phase upon cooling can change into a mixture of two new solid phases, or two solid phases can, upon cooling, react to form a single new phase. These and the other various types of invariant reactions observed in binary systems are listed in Table 1 and illustrated in Fig. 7 and 8.

Table 1 Invariant reactions

Type	Reaction
Eutectic (involves liquid and solid)	L_1 ∨ L_2 >——< S Monotectic
	L ∨ S_1 >——< S_2 Eutectic
	S_1 ∨ L >——< S_2 Catatectic (metatectic)
Eutectoid (involves solid only)	S_1 ∨ S_1 >——< S_2 Monotectoid
	S_1 ∨ S_2 >——< S_3 Eutectoid
Peritectic (involves liquid and solid)	L_1 >——< L_2 Syntectic ^ S
	L >——< S_1 Peritectic ^ S_2
Peritectoid (involves solid only)	S_1 >——< S_2 Peritectoid ^ S_3

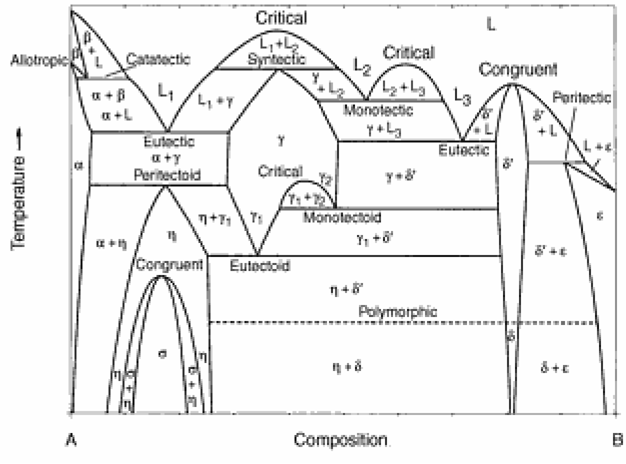

Critical
L
L1+L2
Syntectic
L2
Critical
L2+L3
L3
Congruent
Peritectic
Allotropic
β
β+L
Catatectic
α+β
α+L
L1
L1+γ
γ+L2
Monotectic
γ+L3
δ'+L
δ'+L
L+ε
Eutectic
α+γ
Peritectoid
Eutectic
γ
Critical
γ2
γ1+γ2
γ+δ'
α
δ'
Temperature
α+η
η
η+γ1
γ1
Monotectoid
γ1+δ'
ε
δ'+ε
Congruent
Eutectoid
η+δ'
Polymorphic
σ
η
η+σ
σ+η
η+δ
δ
δ+ε
A
Composition
B

Fig. 7 Hypothetical binary phase diagram showing intermediate phases formed by various invariant reactions and a polymorphic transformation

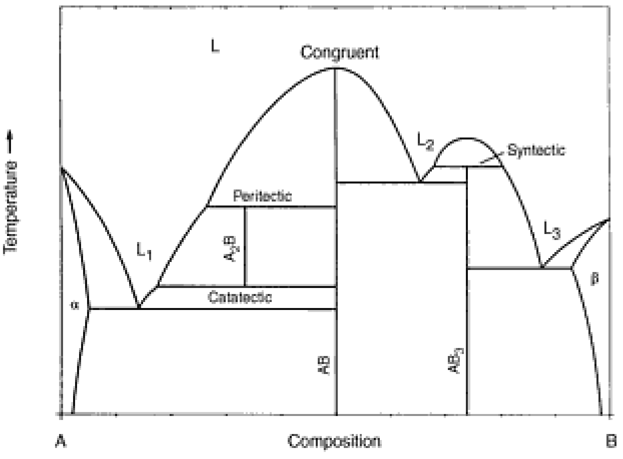

L
Congruent
L2
Syntectic
Peritectic
A2B
L1
L3
β
Catatectic
α
AB
AB3
Temperature
A
Composition
B

Fig. 8 Hypothetical binary phase diagram showing three intermetallic line compounds and four melting reactions

Intermediate Phases. In addition to the three solid terminal-phase fields, α, β, and ε, the diagram in Fig. 7 displays five other solid-phase fields, γ, δ, δ', n, and σ, at intermediate compositions. Such phases are called *intermediate phases.* Many intermediate phases have fairly wide ranges of homogeneity, such as those illustrated in Fig. 7. However, many others have very limited or no significant homogeneity range.

When an intermediate phase of limited (or no) homogeneity range is located at or near a specific ratio of component elements that reflects the normal positioning of the component atoms in the crystal structure of the phase, it is often called a compound (or *line compound*). When the components of the system are metallic, such an intermediate phase is often called an *intermetallic compound.* (Intermetallic compounds should not be confused with chemical compounds, where the type of bonding is different than in crystals and where the ratio has chemical significance.) Three intermetallic compounds (with four types of melting reactions) are shown in Fig. 8.

In the hypothetical diagram shown in Fig. 8, an alloy of composition AB will freeze and melt isothermally, without the liquid or solid phases undergoing changes in composition; such a phase change is called *congruent.* All other reactions are *incongruent;* that is, two phases are formed from one phase on melting. Congruent and incongruent phase changes, however, are not limited to line compounds: the terminal component B (pure phase ε) and the highest-melting composition of intermediate phase δ' in Fig. 7, for example, freeze and melt congruently, while δ' and ε freeze and melt incongruently at other compositions.

Metastable Equilibrium. In Fig. 6(c), dashed lines indicate the portions of the liquidus and solidus lines that disappear into the two-phase solid region. These dashed lines represent valuable information, as they indicate conditions that would exist under metastable equilibrium, such as might theoretically occur during extremely rapid cooling. Metastable extensions of some stable equilibria lines also appear in Fig. 2 and 6(b).

Ternary Diagrams

When a third component is added to a binary system, illustrating equilibrium conditions in two dimensions becomes more complicated. One option is to add a third composition dimension to the base, forming a solid diagram having binary diagrams as its vertical sides. This can be represented as a modified isometric projection, such as shown in Fig. 9. Here, boundaries of single-phase fields (liquidus, solidus, and solvus lines in the binary diagrams) become surfaces; single- and two-phase areas become volumes; three-phase lines become volumes; and four-phase points, while not shown in Fig. 9, can exist as an invariant plane. The composition of a binary eutectic liquid, which is a point in a two-component system, becomes a line in a ternary diagram, as shown in Fig. 9.

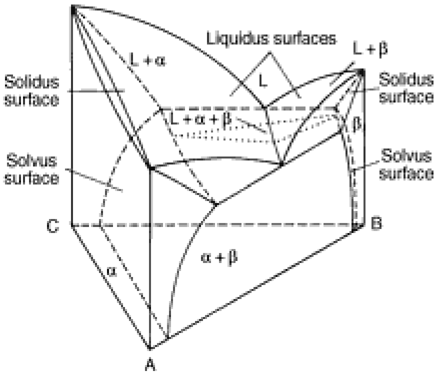


Fig. 9 Ternary phase diagram showing three-phase equilibrium. Source: Ref 1

While three-dimension projections can be helpful in understanding the relationships in the diagram, reading values from them is difficult. Ternary systems, therefore, are often represented by views of the binary diagrams that comprise the faces and two-dimensional projections of the liquidus and solidus surfaces, along with a series of two-dimensional horizontal sections (*isotherms*) and vertical sections (*isopleths*) through the solid diagram.

Vertical sections are often taken through one corner (one component) and a congruently melting binary compound that appears on the opposite face; when such a plot can be read like any other true binary diagram, it is called a quasi-binary section. One possibility of such a section is illustrated by line 1-2 in the isothermal section shown in Fig. 10. A vertical section between a congruently melting binary compound on one face and one on a different face might also form a quasi-binary section (see line 2-3).

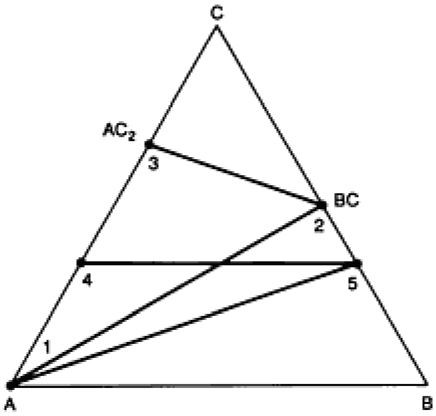


Fig. 10 Isothermal section of a ternary diagram with phase boundaries deleted for simplification

All other vertical sections are not true binary diagrams, and the term *pseudobinary* is applied to them. A common pseudobinary section is one where the percentage of one of the components is held constant (the section is parallel to one of the faces), as shown by line 4-5 in Fig. 10. Another is one where the ratio of two constituents is held constant, and the amount of the third is varied from 0 to 100% (line 1-5).

Isothermal Sections. Composition values in the triangular isothermal sections are read from a triangular grid consisting of three sets of lines parallel to the faces and placed at regular composition intervals (see Fig. 11). Normally, the point of the triangle is placed at the top of the illustration, component A is placed at the bottom left, B at the bottom right, and C at the top. The amount of constituent A is normally indicated from point C to point A, the amount of constituent B from point A to point B, and the amount of constituent C from point B to point C. This scale arrangement is often modified when only a corner area of the diagram is shown.

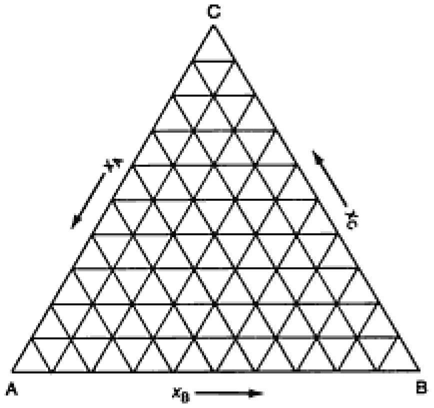


Fig. 11 Triangular composition grid for isothermal sections; *X* is the composition of each constituent in mole fraction or percent

Projected Views. Liquidus, solidus, and solvus surfaces by their nature are not isothermal. Therefore, equal-temperature (isothermal) contour lines are often added to the projected views of these surfaces to indicate the shape of the surfaces (see Fig. 12). In addition to (or instead of) contour lines, views often show lines indicating the temperature troughs (also called "valleys" or "grooves") formed at the intersections of two surfaces. Arrowheads are often added to these lines to indicate the direction of decreasing temperature in the trough.

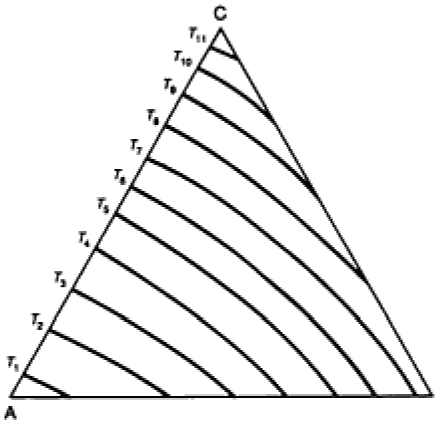


Fig. 12 Liquidus projection of a ternary phase diagram showing isothermal contour lines. Source: adapted from Ref 1

Reference cited in this section

1. F.N. Rhines, *Phase Diagrams in Metallurgy: Their Development and Application,* McGraw-Hill, 1956

Thermodynamic Principles

The reactions between components, the phases formed in a system, and the shape of the resulting phase diagram can be explained and understood through knowledge of the principles, laws, and terms of thermodynamics, and how they apply to the system.

Table 2 Composition conversions

The following equations can be used to make conversions in binary systems:

$$\text{wt\% A} = \frac{\text{at.\% A} \times \text{at. wt of A}}{(\text{at.\% A} \times \text{at. wt of A}) + (\text{at.\% B} \times \text{at. wt of B})} \times 100$$

$$\text{at.\% A} = \frac{\text{wt\% A/at. wt of A}}{(\text{at.\% A/at. wt of A}) + (\text{wt\% B/at. wt of B})} \times 100$$

The equation for converting from atomic percentages to weight percentages in higher-order systems is similar to that for binary systems, except that an additional term is added to the denominator for each additional component. For ternary systems, for example:

$$\text{wt\% A} = \frac{\text{at.\% A} \times \text{at. wt of A}}{(\text{at.\% A} \times \text{at. wt of A}) + (\text{at.\% B} \times \text{at. wt of B}) + (\text{at.\% C} \times \text{at. wt of C})} \times 100$$

$$\text{at.\% A} = \frac{\text{wt\% A/at. wt of A}}{(\text{wt\% A/at. wt of A}) + (\text{wt\% B/at. wt of B}) + (\text{wt\% C/at. wt of C})} \times 100$$

The conversion from weight to atomic percentages for higher-order systems is easy to accomplish on a computer with a spreadsheet program.

Internal Energy. The sum of the kinetic energy (energy of motion) and potential energy (stored energy) of a system is called its *internal energy, E.* Internal energy is characterized solely by the state of the system.

Closed System. A thermodynamic system that undergoes no interchange of mass (material) with its surroundings is called a *closed system.* A closed system, however, can interchange energy with its surroundings.

First Law. The *First Law of Thermodynamics,* as stated by Julius von Mayer, James Joule, and Hermann von Helmholtz in the 1840s, says that "energy can be neither created nor destroyed." Therefore, it is called the "Law of Conservation of Energy." This law means the total energy of an isolated system remains constant throughout any operations that are carried out on it; that is for any quantity of energy in one form that disappears from the system, an equal quantity of another form (or other forms) will appear.

For example, consider a closed gaseous system to which a quantity of heat energy, δQ, is added and a quantity of work, δW, is extracted. The First Law describes the change in internal energy, dE, of the system as follows:

$$dE = \delta Q - \delta W$$

In the vast majority of industrial processes and material applications, the only work done by or on a system is limited to pressure/volume terms. Any energy contributions from electric, magnetic, or gravitational fields are neglected, except for electrowinning and electrorefining processes such as those used in the production of copper, aluminum, magnesium, the alkaline metals, and the alkaline earth metals. With the neglect of field effects, the work done by a system can be measured by summing the changes in volume, dV, times each pressure causing a change. Therefore, when field effects are neglected, the First Law can be written:

$$dE = \delta Q - PdV$$

Enthalpy. Thermal energy changes under constant pressure (again neglecting any field effects) are most conveniently expressed in terms of the *enthalpy, H,* of a system. Enthalpy, also called *heat content,* is defined by:

$$H = E + PV$$

Enthalpy, like internal energy, is a function of the state of the system, as is the product PV.

Heat Capacity. The *heat capacity, C,* of a substance is the amount of heat required to raise its temperature one degree, that is:

$$C = \frac{\delta Q}{dT}$$

However, if the substance is kept at constant volume ($dV = 0$):

$$\delta Q = dE$$

and

$$C_v = \left(\frac{\delta Q}{\delta T}\right)_v = \left(\frac{dE}{dT}\right)_v$$

If, instead, the substance is kept at constant pressure (as in many metallurgical systems):

$$C_p = \left(\frac{dE}{dT}\right) + \left(\frac{PdV}{dT}\right)_p$$

and

$$C_p = \left[\frac{d(E + PV)}{dT}\right]_p$$

$$C_p = \left(\frac{dH}{dT}\right)_p$$

Second Law. While the First Law establishes the relationship between the heat absorbed and the work performed by a system, it places no restriction on the source of the heat or its flow direction. This restriction, however, is set by the *Second Law of Thermodynamics,* which was advanced by Rudolf Clausius and William Thomson (Lord Kelvin). The Second Law says that "the spontaneous flow of heat always is from the higher temperature body to the lower temperature body." In other words, "all naturally occurring processes tend to take place spontaneously in the direction that will lead to equilibrium."

Entropy. The Second Law is most conveniently stated in terms *entropy, S,* another property of state possessed by all systems. Entropy represents the energy (per degree of absolute temperature, *T*) in a system that is not available for work. In terms of entropy, the Second Law says that "all natural processes tend to occur only with an increase in entropy, and the direction of the process always is such as to lead to an increase in entropy." For processes taking place in a system in equilibrium with its surroundings, the change in entropy is defined as follows:

$$dS \equiv \frac{\delta Q}{T} = \frac{dE + PdV}{T}$$

Third Law. A principle advanced by Theodore Richards, Walter Nernst, Max Planck, and others, often called the *Third Law of Thermodynamics,* states that "the entropy of all chemically homogeneous materials can be taken as zero at absolute zero temperature" (0 K). This principle allows calculation of the absolute values of entropy of pure substances solely from heat capacity.

Gibbs Energy. Because both *S* and *V* are difficult to control experimentally, an additional term, *Gibbs energy, G,*is introduced, whereby:

$$G \equiv E + PV - TS \equiv H - TS$$

and

$$dG = dE + PdV + VdP - TdS - SdT$$

However,

$$dE = TdS - PdV$$

Therefore,

$$dG = VdP - SdT$$

Here, the change in Gibbs energy of a system undergoing a process is expressed in terms of two independent variables--pressure and absolute temperature--which are readily controlled experimentally. If the process is carried out under conditions of constant pressure and temperature, the change in Gibbs energy of a system at equilibrium with its surroundings (a reversible process) is zero. For a spontaneous (irreversible) process, the change in Gibbs energy is less than zero (negative); that is, the Gibbs energy decreases during the process, and it reaches a minimum at equilibrium.

Thermodynamics and Phase Diagrams

The areas (fields) in a phase diagram, and the position and shapes of the points, lines, surfaces, and intersections in it, are controlled by thermodynamic principles and the thermodynamic properties of all of the phases that comprise the system.

Phase-Field Rule. The phase rule specifies that at constant temperature and pressure, the number of phases in adjacent fields in a multicomponent diagram must differ by one.

Theorem of Le Châtelier. The *theorem of Henri Le Châtelier,* which is based on thermodynamic principles, says that "if a system in equilibrium is subjected to a constraint by which the equilibrium is altered, a reaction occurs that opposes the constraint, that is, a reaction that partially nullifies the alteration." The effect of this theorem on lines in a phase diagram can be seen in Fig. 2. The slopes of the sublimation line (1) and the vaporization line (3) show that the system reacts to increasing pressure by making the denser phases (solid and liquid) more stable at higher pressure. The slope of the melting line (2) indicates that this hypothetical substance contracts on freezing. (Note that the boundary between liquid water and ordinary ice, which expands on freezing, slopes towards the pressure axis.)

Clausius-Clapeyron Equation. The theorem of Le Châtelier was quantified by Benoit Clapeyron and Rudolf Clausius to give the following equation:

$$\frac{dP}{dT} = \frac{\Delta H}{t\Delta V}$$

where dP/dT is the slope of the univariant lines in a PT diagram such as those shown in Fig. 2, ΔV is the difference in molar volume of the two phases in the reaction, and ΔH is difference in molar enthalpy of the two phases (the heat of the reaction).

Solutions. The shape of liquidus, solidus, and solvus curves (or surfaces) in a phase diagram are determined by the Gibbs energies of the relevant phases. In this instance, the Gibbs energy must include not only the energy of the constituent components, but also the energy of mixing of these components in the phase.

Consider, for example, the situation of complete miscibility shown in Fig. 3. The two phases, solid α and liquid, are in stable equilibrium in the two-phase field between the liquidus and solidus lines. The Gibbs energies at various temperatures are calculated as a function of composition for ideal liquid solutions and for ideal solid solutions of the two components, A and B. The result is a series of plots similar to those in Fig. 13(a) to 13(e).

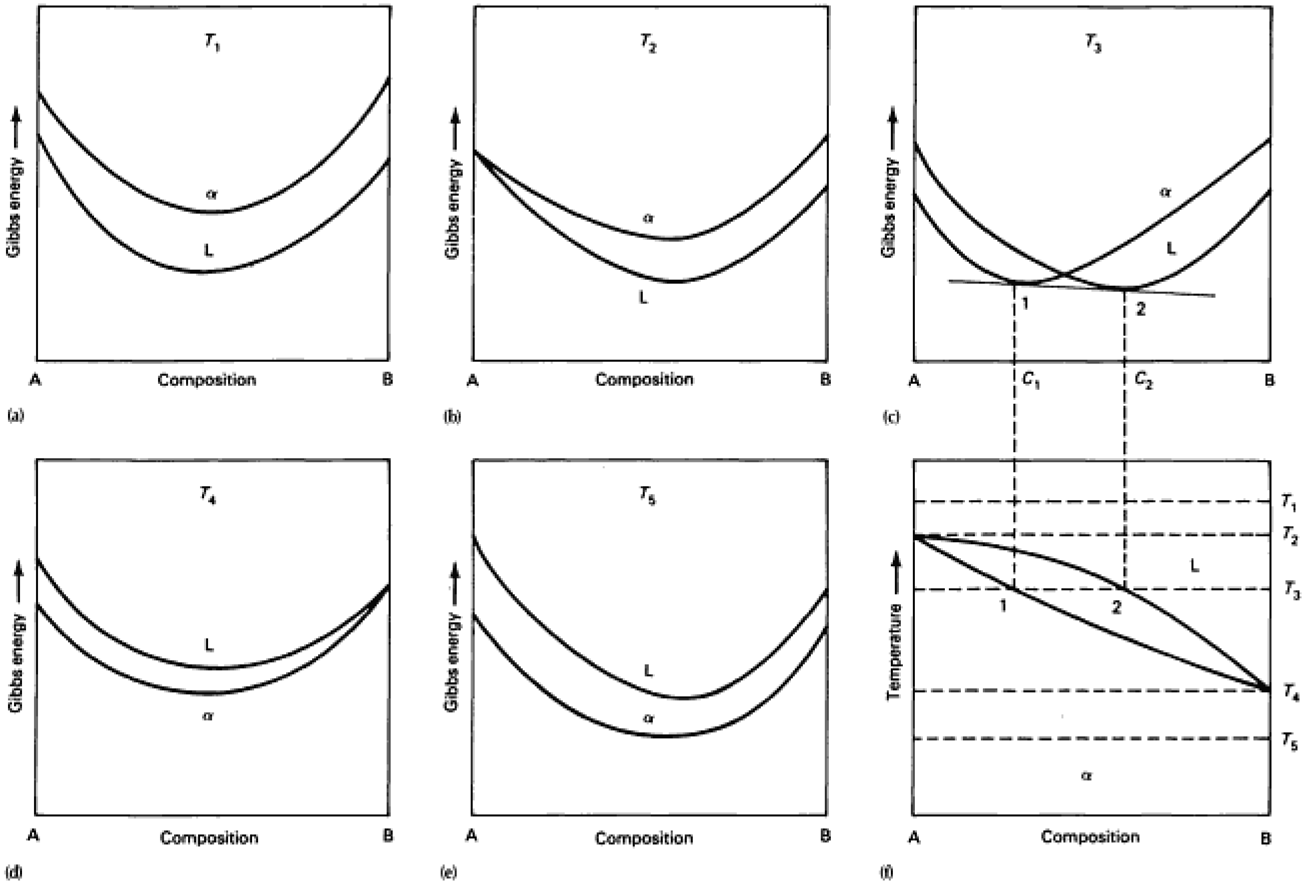


Fig. 13 Use of Gibbs energy curves to construct a binary phase diagram that shows miscibility in both the liquid and solid states. Source: adapted from Ref 2

At temperature T_1, the liquid solution has the lower Gibbs energy and, therefore, is the more stable phase. At T_2, the melting temperature of A, the liquid and solid are equally stable only at a composition of pure A. At temperature T_3, between the melting temperatures of A and B, the Gibbs energy curves cross. Temperature T_4 is the melting temperature of B, while T_5 is below it.

Construction of the two-phase liquid-plus-solid field of the phase diagram in Fig. 13(f) is as follows. According to thermodynamic principles, the compositions of the two phases in equilibrium with each other at temperature T_3 can be determined by constructing a straight line that is tangential to both curves in Fig. 13(c). The points of tangency, 1 and 2, are then transferred to the phase diagram as points on the solidus and liquidus, respectively. This is repeated at sufficient temperatures to determine the curves accurately.

If, at some temperature, the Gibbs energy curves for the liquid and the solid tangentially touch at some point, the resulting phase diagram will be similar to those shown in Fig. 4(a) and 4(b), where a maximum or minimum appears in the liquidus and solidus curves.

Mixtures. The two-phase field in Fig. 13(f) consists of a mixture of liquid and solid phases. As stated above, the compositions of the two phases in equilibrium at temperature T_3 are C_1 and C_2. The horizontal isothermal line connecting points 1 and 2, where these compositions intersect temperature T_3, is called a *tie line.* Similar tie lines connect the coexisting phases throughout all two-phase fields (areas) in binary and (volumes) in ternary systems, while *tie triangles* connect the coexisting phases throughout all three-phase regions (volumes) in ternary systems.

Eutectic phase diagrams, a feature of which is a field where there is a mixture of two solid phases, also can be constructed from Gibbs energy curves. Consider the temperatures indicated on the phase diagram in Fig. 14(f) and the Gibbs energy curves for these temperatures (Fig. 14a to 14e). When the points of tangency on the energy curves are transferred to the diagram, the typical shape of a eutectic system results. The mixture of solid α and β that forms upon cooling through the eutectic point 10 has a special microstructure, as discussed later.

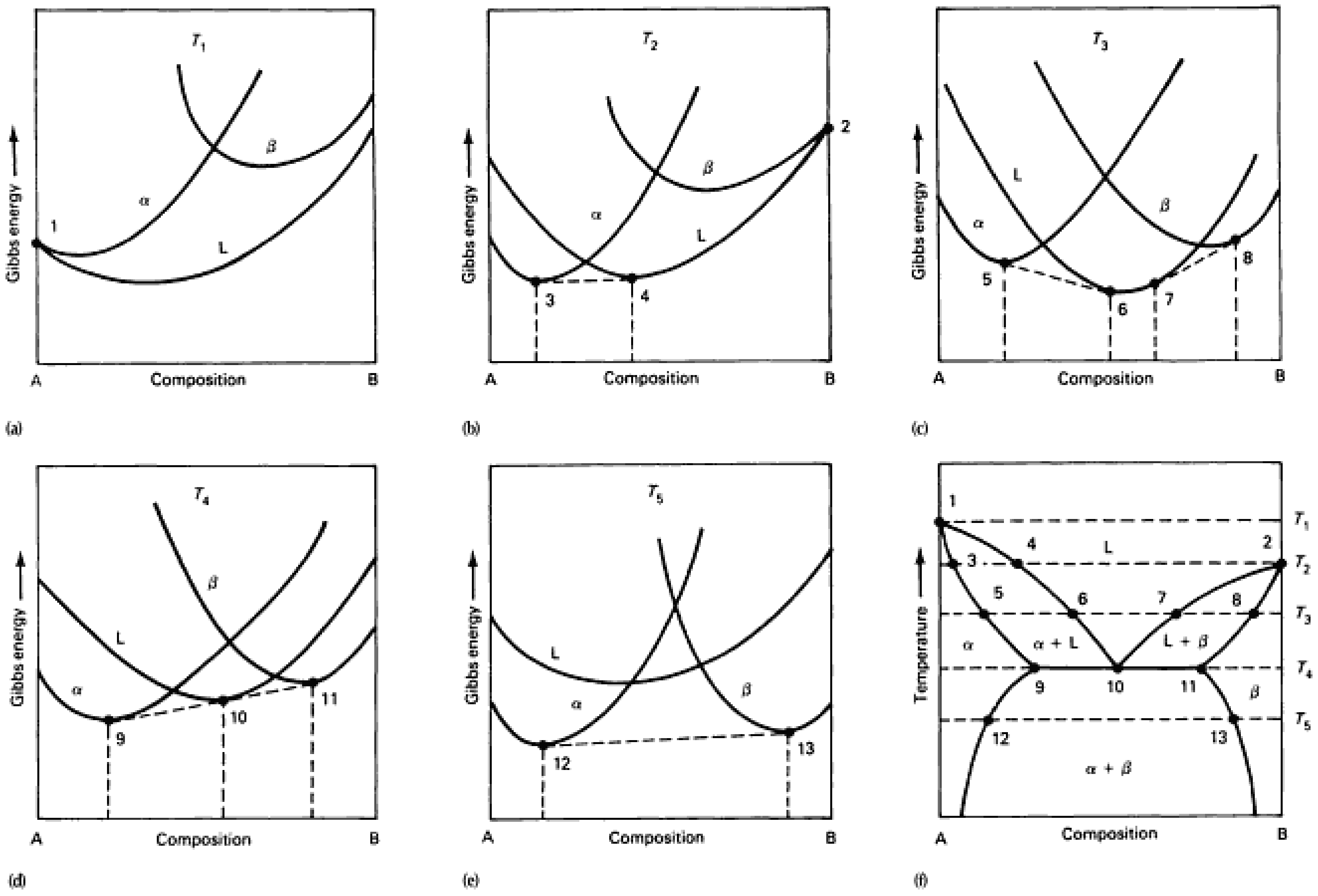

T₁
β
α
1
L
Gibbs energy
A
Composition
B
(a)
T₂
2
β
α
L
3
4
Gibbs energy
A
Composition
B
(b)
T₃
L
β
α
5
6
7
8
Gibbs energy
A
Composition
B
(c)
T₄
β
L
α
9
10
11
Gibbs energy
A
Composition
B
(d)
T₅
L
α
β
12
13
Gibbs energy
A
Composition
B
(e)
1
4
L
2
T₁
3
T₂
5
6
7
8
T₃
α
α + L
L + β
T₄
9
10
11
β
T₅
12
13
α + β
Temperature
A
Composition
B
(f)

Fig. 14 Use of Gibbs energy curves to construct a binary phase diagram of the eutectic type. Source: adapted from Ref 3

Binary phase diagrams that have three-phase reactions other than the eutectic reaction, as well as diagrams with multiple three-phase reactions, also can be constructed from appropriate Gibbs energy curves. Likewise, Gibbs energy surfaces and tangential planes can be used to construct ternary phase diagrams.

Curves and Intersections. Thermodynamic principles also limit the shape of the various boundary curves (or surfaces) and their intersections. For example, see the *PT* diagram shown in Fig. 2. The Clausius-Clapeyron equation requires that at the intersection of the triple curves in such a diagram, the angle between adjacent curves should never exceed 180°, or alternatively, the extension of each triple curve between two phases must lie within the field of third phase.

The angle at which the boundaries of two-phase fields meet also is limited by thermodynamics. That is, the angle must be such that the extension of each beyond the point of intersection projects into a two-phase field, rather than a one-phase field. An example of correct intersections can be seen in Fig. 6(b), where both the solidus and solvus lines are concave. However, the curvature of both boundaries need not be concave.

Congruent Transformations. The *congruent point* on a phase diagram is where different phases of same composition are in equilibrium. The *Gibbs-Konovalov Rule* for congruent points, which was developed by Dmitry Konovalov from a thermodynamic expression given by J. Willard Gibbs, states that the slope of phase boundaries at congruent transformations must be zero (horizontal). Examples of correct slope at the maximum and minimum points on liquidus and solidus curves can be seen in Fig. 4.

Higher-Order Transitions. The transitions considered in this article up to now have been limited to the common thermodynamic types called *first-order transitions,* that is, changes involving distinct phases having different lattice parameters, enthalpies, entropies, densities, and so forth. Transitions not involving discontinuities in composition, enthalpy, entropy, or molar volume are called *higher-order transitions* and occur less frequently. The change in the magnetic quality of iron from ferromagnetic to paramagnetic as the temperature is raised above 771 °C (1420 °F) is an example of a second-order transition: no phase change is involved and the Gibbs phase rule does not come into play in the transition.

Another example of a higher-order transition is the continuous change from a random arrangement of the various kinds of atoms in a multicomponent crystal structure (a *disordered structure*) to an arrangement where there is some degree of *crystal ordering* of the atoms (an *ordered structure,* or *superlattice*), or the reverse reaction.

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Reading Phase Diagrams

Composition Scales. Phase diagrams to be used by scientists are usually plotted in atomic percentage (or mole fraction), while those to be used by engineers are usually plotted in weight percentage. Conversions between weight and atomic composition also can be made using the equations given in Table 2 and standard atomic weights listed in the periodic table (the periodic table and atomic weights of the elements can be found in the article entitled "The Chemical Elements" in this Section).

Lines and Labels. Magnetic transitions (Curie temperature and Néel temperature) and uncertain or speculative boundaries are usually shown in phase diagrams as nonsolid lines of various types.

The components of metallic systems, which usually are pure elements, are identified in phase diagrams by their symbols. Allotropes of polymorphic elements are distinguished by small (lower-case) Greek letter prefixes.

Terminal solid phases are normally designated by the symbol (in parentheses) for the allotrope of the component element, such as (Cr) or (αTi). Continuous solid solutions are designated by the names of both elements, such as (Cu,Pd) or (βTi, βY).

Intermediate phases in phase diagrams are normally labeled with small (lower-case) Greek letters. However, certain Greek letters are conventionally used for certain phases, particularly disordered solutions: for example, βfor disordered body-centered cubic (bcc), ζor ε for disordered close-packed hexagonal (cph), γ for the γ-brass-type structure, and σ for the σCrFe-type structure.

For line compounds, a stoichiometric phase name is used in preference to a Greek letter (for example, A_2B_3 rather than δ). Greek letter prefixes are used to indicate high- and low-temperature forms of the compound (for example, αA_2B_3 for the low-temperature form and βA_2B_3 for the high-temperature form).

Lever Rule. As explained in the section on "Thermodynamics and Phase Diagrams," a tie line is an imaginary horizontal line drawn in a two-phase field connecting two points that represent two coexisting phases in equilibrium at the temperature indicated by the line. Tie lines can be used to determine the fractional amounts of the phases in equilibrium by employing the *lever rule.* The lever rule is a mathematical expression derived by the principle of conservation of matter in which the phase amounts can be calculated from the bulk composition of the alloy and compositions of the conjugate phases, as shown in Fig. 15(a).

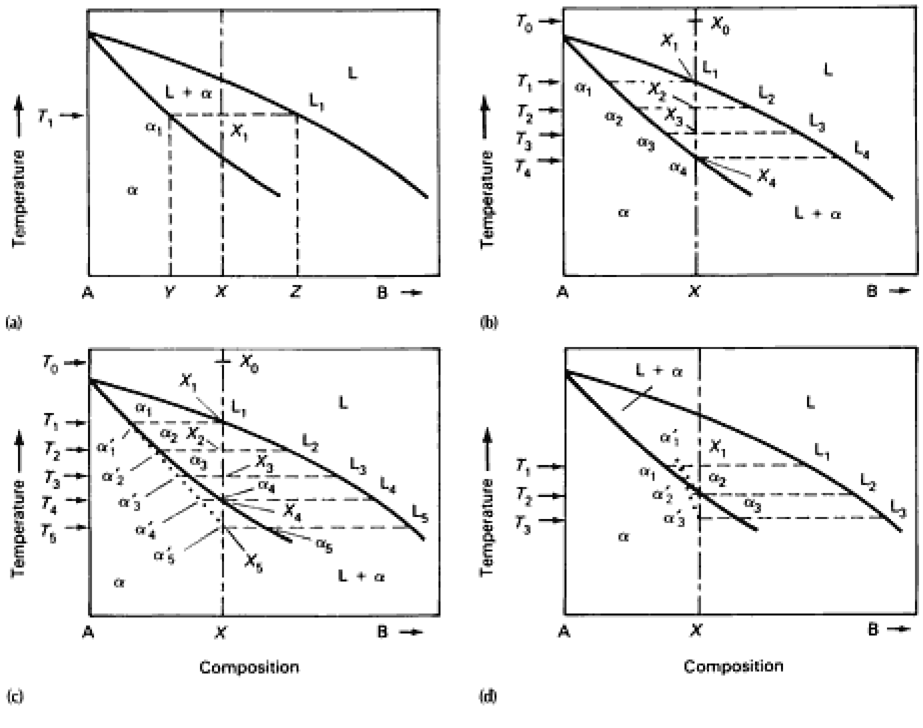


Fig. 15 Portion of a binary phase diagram containing a two-phase liquid-plus-solid field illustrating (a) application of the lever rule to (b) equilibrium freezing, (c) nonequilibrium freezing, and (d) heating of a homogenized sample. Source: Ref 1

At the left end of the line between α_1 and L_1, the bulk composition is Y% component B and 100 - Y% component A, and consists of 100% α solid solution. As the percentage of component B in the bulk composition moves to the right, some liquid appears along with the solid. With further increases in the amount of B in the alloy, more of the mixture consists of liquid, until the material becomes entirely liquid at the right end of the tie line. At bulk composition X, which is less than halfway to point L_1, there is more solid present than liquid. The lever rule says that the percentages of the two phases present can be calculated as follows:

$$\%\ \text{liquid} = \frac{\text{Length of line } \alpha_1 X_1}{\text{Length of line } \alpha_1 L_1} \times 100$$

$$\%\ \text{solid } \alpha = \frac{\text{Length of line } X_1 L_1}{\text{Length of line } \alpha_1 L_1} \times 100$$

It should be remembered that the calculated amounts of the phases present are either in weight or atomic percentages, and as shown in Table 3, do not directly indicate the area or volume percentages of the phases observed in microstructures.

Table 3 Volume fraction

In order to relate the weight fraction of a phase present in an alloy specimen as determined from a phase diagram to its two-dimensional appearance as observed in a micrograph, it is necessary to be able to convert between weight-fraction values and area-fracture values, both in decimal fractions. This conversion can be developed as follows:
The weight fraction of the phase is determined from the phase diagram, using the lever rule.
Volume portion of the phase = (Weight fraction of the phase)/(Phase density)
Total volume of all phases present = Sum of the volume portions of each phase.
Volume fraction of the phase = (Weight fraction of the phase)/(Phase density × total volume)
It has been shown by stereology and quantitative metallography that areal fraction is equal to volume fraction (Ref 6). (Areal fraction of a phase is the sum of areas of the phase intercepted by a microscopic traverse of the observed region of the specimen divided by the total area of the observed region.) Therefore:
Areal fraction of the phase = (Weight fraction of the phase)/(Phase density × total volume)
The phase density value for the preceding equation can be obtained by measurements or calculation. The densities of chemical elements, and some line compounds, can be found in the literature. Alternatively, the density of a unit cell of a phase comprising one or more elements can be calculated from information about its crystal structure and the atomic weights of the elements comprising it as follows:

Total cell weight = Sum of weights of each element
Density = Total cell weight/cell volume
For example, the calculated density of pure copper, which has a fcc structure and a lattice parameter of 0.36146 nm, is:
$\rho = \frac{4 \text{ atoms/cell } \times 63.546 \text{ g/mol}}{6.0227 \times 10^{23} \text{ atoms/mol} \times (0.36146 \times 10^{-9} \text{ m})^3}$ $= 8.937 \text{ Mg/m}^3$

Phase-Fraction Lines. Reading the phase relationships in many ternary diagram sections (and other types of sections) often can be difficult due to the great many lines and areas present. *Phase-fraction lines* are used by some to simplify this task. In this approach, the sets of often nonparallel tie lines in the two-phase fields of isothermal sections (see Fig. 16a) are replaced with sets of curving lines of equal phase fraction (Fig. 16b). Note that the phase-fraction lines extend through the three-phase region where they appear as a triangular network. As with tie lines, the number of phase-fraction lines used is up to the individual using the diagram. While this approach to reading diagrams may not seem helpful for such a simple diagram, it can be a useful aid in more complicated systems. For more information on this topic, see Ref 4 and 5.

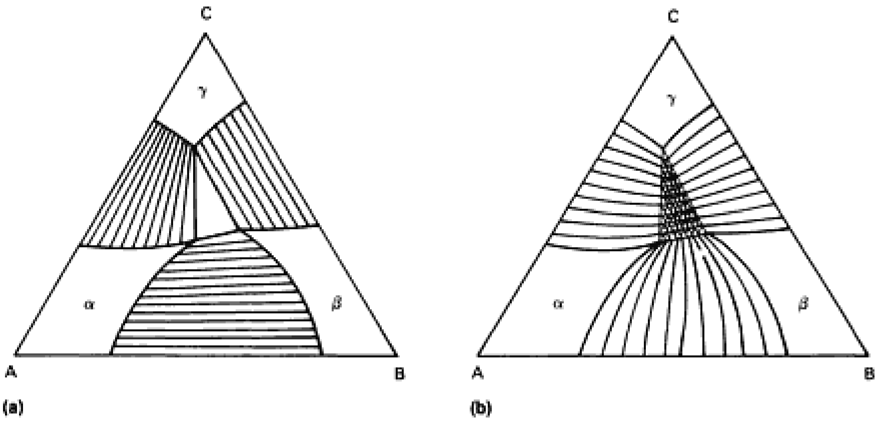


Fig. 16 Alternative systems for showing phase relationships in multiphase regions of ternary-diagram isothermal sections. (a) Tie lines. (b) Phase-fraction lines. Source: Ref 4

Solidification. Tie lines and the lever rule can be used to understand the freezing of a solid-solution alloy. Consider the series of tie lines at different temperature shown in Fig. 15(b), all of which intersect the bulk composition X. The first crystals to freeze have the composition α_1. As the temperature is reduced to T_2 and the solid crystals grow, more A atoms are removed from the liquid than B atoms, thus shifting the composition of the remaining liquid to composition L_2. Therefore, during freezing, the compositions of both the layer of solid freezing out on the crystals and the remaining liquid continuously shift to higher B contents and become leaner in A. Therefore, for equilibrium to be maintained, the solid crystals must absorb B atoms from the liquid and B atoms must migrate (diffuse) from the previously frozen material into subsequently deposited layers. When this happens, the average composition of the solid material follows the solidus line to temperature T_4 where it equals the bulk composition of the alloy.

Coring. If cooling takes place too rapidly for maintenance of equilibrium, the successive layers deposited on the crystals will have a range of local compositions from their centers to their edges (a condition known as *coring*). Development of this condition is illustrated in Fig. 15(c). Without diffusion of B atoms from the material that solidified at temperature T_1 into the material freezing at T_2, the average composition of the solid formed up to that point will not follow the solidus line. Instead it will remain to the left of the solidus, following compositions α'_1 through α'_3. Note that final freezing does not occur until temperature T_5, which means that nonequilibrium solidification takes place over a greater temperature range than equilibrium freezing. Because most metals freeze by the formation and growth of "treelike" crystals, called *dendrites,* coring is sometimes called *dendritic segregation.* An example of cored dendrites is shown in Fig. 17.

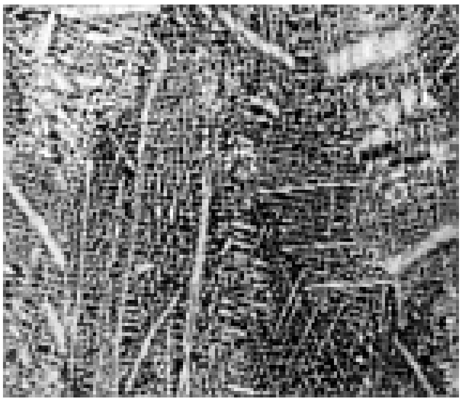


Fig. 17 Copper alloy 71500 (Cu-30Ni) ingot. Dendritic structure shows coring: light areas are nickel-rich; dark areas are low in nickel. 20×. Source: Ref 6

Liquation. Because the lowest freezing material in a cored microstructure is segregated to the edges of the solidifying crystals (the grain boundaries), this material can remelt when the alloy sample is heated to temperatures below the equilibrium solidus line. If grain-boundary melting (called *liquation* or "burning") occurs while the sample also is under stress, such as during hot forming, the liquefied grain boundaries will rupture and the sample will lose its ductility and be characterized as *hot short.*

Liquation also can have a deleterious effect on the mechanical properties (and microstructure) of the sample after it returns to room temperature. This is illustrated in Fig. 15(d) for a homogenized sample. If homogenized alloy X is heated into the liquid-plus-solid region for some reason (inadvertently or during welding, etc.), it will begin to melt when it reaches temperature T_2; the first liquid to appear will have the composition L_2. When the sample is heated at normal rates to temperature T_1, the liquid formed so far will have a composition L_1, but the solid will not have time to reach the equilibrium composition α_1. The average composition will instead lie at some intermediate value such as α'_1. According to the lever rule, this means that less than the equilibrium amount of liquid will form at this temperature. If the sample is then rapidly cooled from temperature T_1, solidification will occur in the normal manner, with a layer of material having composition α_1 deposited on existing solid grains. This is followed by layers of increasing B content up to composition α_3 at temperature T_3, where all of the liquid is converted to solid. This produces coring in the previously melted regions along the grain boundaries and sometimes even voids that decrease the strength of the sample. Homogenization heat treatment will eliminate the coring, but not the voids.

Eutectic Microstructures. When an alloy of eutectic composition is cooled from the liquid state, the eutectic reaction occurs at the eutectic temperature, where the two distinct liquidus curves meet. At this temperature, both α and β solid phases must deposit on the grain nuclei until all of the liquid is converted to solid. This simultaneous deposition results in microstructures made up of distinctively shaped particles of one phase in a matrix of the other phase, or alternate layers of the two phases. Examples of characteristic eutectic microstructures include spheroidal, nodular, or globular; acicular (needles) or rod; and lamellar (platelets, Chinese script or dendritic, or filigreed). Each eutectic alloy has its own characteristic microstructure, when slowly cooled (see Fig. 18). Cooling more rapidly, however, can affect the microstructure obtained (see Fig. 19). Care must be taken in characterizing eutectic structures because elongated particles can appear nodular and flat platelets can appear elongated or needlelike when viewed in cross section.

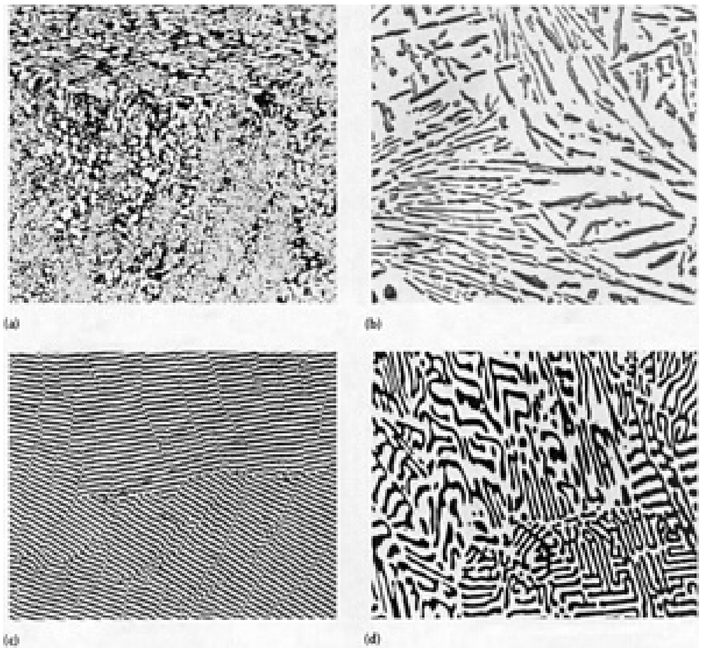


Fig. 18 Examples of characteristic eutectic microstructures in slowly cooled alloys. (a) 40Sn-50In alloy showing globules of tin-rich intermetallic phase (light) in a matrix of dark indium-rich intermetallic phase. 150×. (b) Al-13Si alloy showing an acicular structure consisting of short, angular particles of silicon (dark) in a matrix of aluminum. 200×. (c) Al-33Cu alloy showing a lamellar structure consisting of dark platelets of $CuAl_2$ and light platelets of aluminum solid solution. 180×. (d) Mg-37Sn alloy showing a lamellar structure consisting of Mg_2Sn "Chinese-script" (dark) in a matrix of magnesium solid solution. 250×. Source: Ref 6

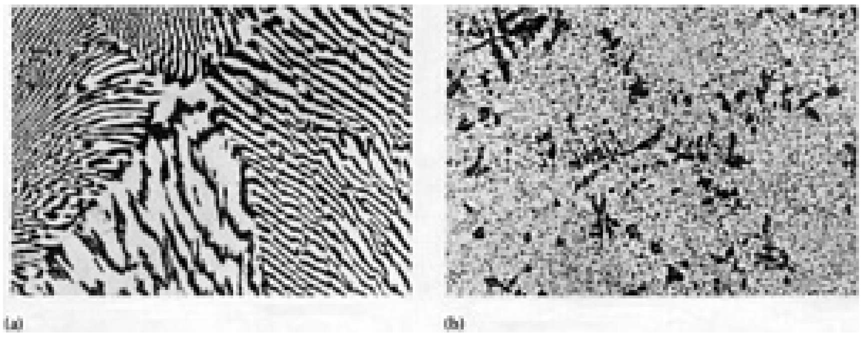


Fig. 19 Effect of cooling rate on the microstructure of Sn-37Pb alloy (eutectic soft solder). (a) Slowly cooled sample shows a lamellar structure consisting of dark platelets of lead-rich solid solution and light platelets of tin. 375×. (b) More rapidly cooled sample shows globules of lead-rich solid solution, some of which exhibit a slightly dendritic structure, in a matrix of tin. 375×. Source: Ref 6

If the alloy has a composition different than the eutectic composition, the alloy will begin to solidify before the eutectic temperature is reached. If the alloy is hypoeutectic, some dendrites of will form in the liquid before the remaining liquid solidifies at the eutectic temperature. If the alloy is hypereutectic, the first (primary) material to solidify will be dendrites of . The microstructure produced by slow cooling of a hypoeutectic and hypereutectic alloy will consist of relatively large particles of *primary constituent*, consisting of the phase that begins to freeze first surrounded by relatively fine eutectic structure. In many instances, the shape of the particles will show a relationship to their dendritic origin (see Fig. 20a). In other instances, the initial dendrites will have filled out somewhat into *idiomorphic particles* (particles having their own characteristic shape) that reflect the crystal structure of the phase (see Fig. 20b).

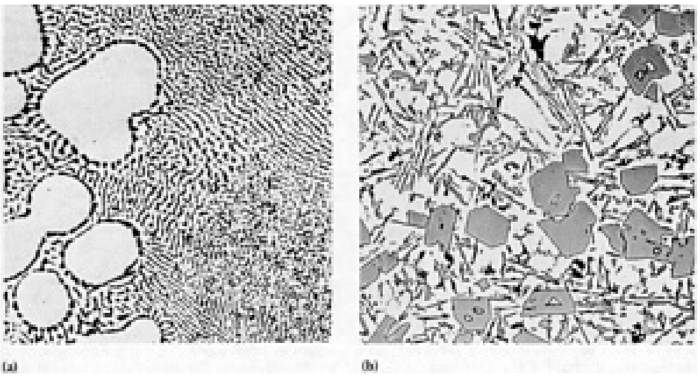


Fig. 20 Examples of primary-particle shape. (a) Sn-30Pb hypoeutectic alloy showing dendritic particles of tin-rich solid solution in a matrix of tin-lead eutectic. 500×. (b) Al-19Si hypereutectic alloy, phosphorus-modified, showing idiomorphic particles of silicon in a matrix of aluminum-silicon eutectic. 100×. Source: Ref 6

As stated earlier, cooling at a rate that does not allow sufficient time to reach equilibrium conditions will affect the resulting microstructure. For example, it is possible for an alloy in a eutectic system to obtain some eutectic structure in an alloy outside the normal composition range for such a structure. This is illustrated in Fig. 21. With relatively rapid cooling of alloy *X*, the composition of the solid material that forms will follow line $_1$ - $'_4$ rather than solidus line to $_4$. As a result, the last liquid to solidify will have the eutectic composition L_4 rather than L_3, and will form some eutectic structure in the microstructure. The question of what takes place when the temperature reaches T_5 is discussed later.

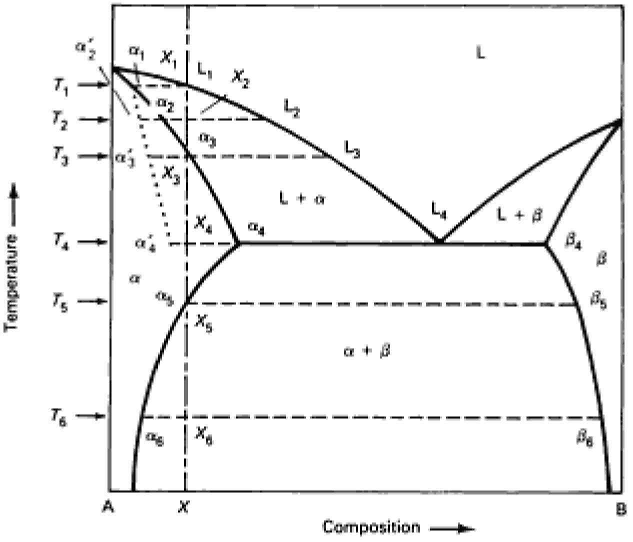


Fig. 21 Binary phase diagram, illustrating the effect of cooling rate on an alloy lying outside the equilibrium eutectic-transformation line. Rapid solidification into a terminal phase field can result in some eutectic structure being formed; homogenization at temperatures in the single-phase field will eliminate the eutectic structure; phase will precipitate out of solution upon slow cooling into the -plus- field. Source: adapted from Ref 1

Eutectoid Microstructures. Because the diffusion rates of atoms are so much lower in solids than liquids, nonequilibrium transformation is even more important in solid/solid reactions (such as the eutectoid reaction) than in liquid/solid reactions (such as the eutectic reaction). With slow cooling through the eutectoid temperature, most alloys of eutectoid composition such as alloy 2 in Fig. 22 transform from a single-phase microstructure to a lamellar structure consisting of alternate platelets of and arranged in groups (or "colonies"). The appearance of this structure is very similar to lamellar eutectic structure (see Fig. 23). When found in cast irons and steels, this structure is called "pearlite" because of its shiny mother-of-pearl-like appearance under the microscope (especially under oblique illumination); when similar eutectoid structure is found in nonferrous alloys, it often is called "pearlite-like" or "pearlitic."

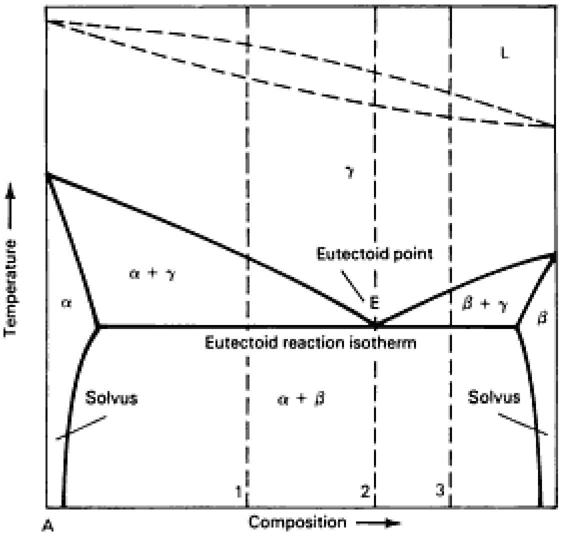


Fig. 22 Binary phase diagram of a eutectoid system. Source: adapted from Ref 1

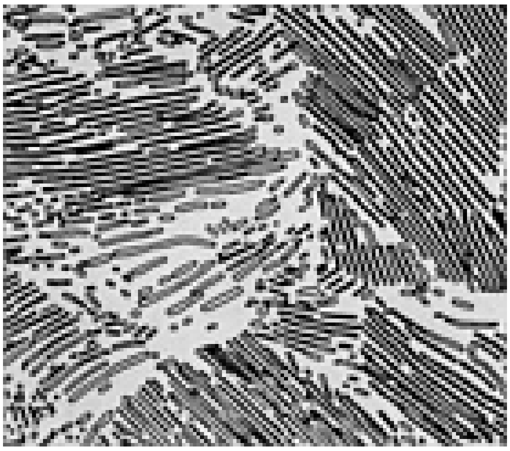


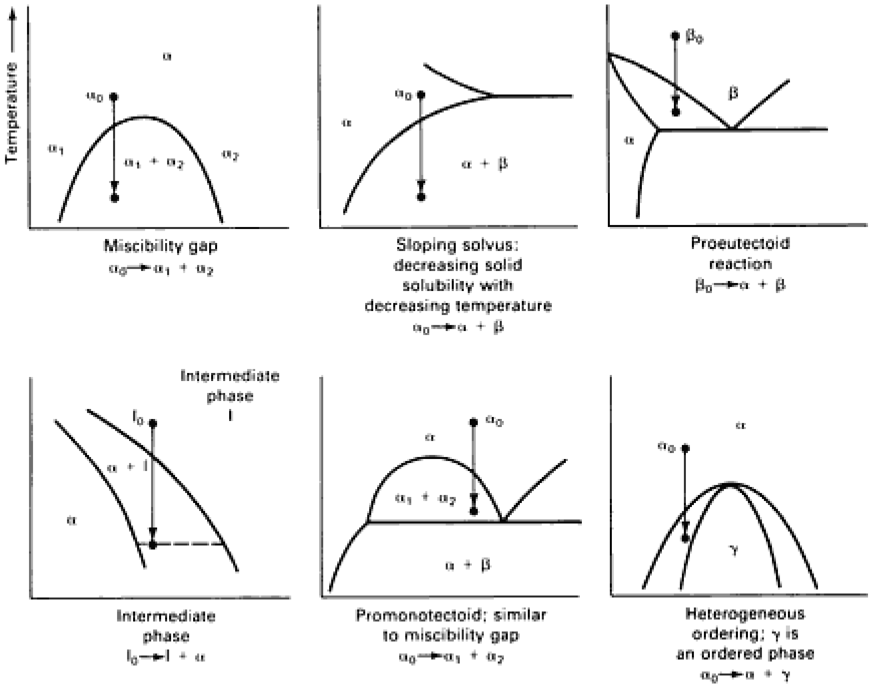
Fig. 23 Fe-0.8C alloy showing a typical pearlite eutectoid structure of alternate layers of light ferrite and dark cementite. 500×. Source: Ref 6

The terms, *hypoeutectoid* and *hypereutectoid* have the same relationship to the eutectoid composition as hypoeutectic and hypereutectic do in a eutectic system; alloy 1 in Fig. 22 is a hypoeutectoid alloy, while alloy 3 is hypereutectoid. The solid-state transformation of such alloys takes place in two steps, much like freezing of hypoeutectic and hypereutectic alloys except that the microconstituents that form before the eutectoid temperature is reached are referred to as *proeutectoid constituents* rather than "primary."

Microstructures of Other Invariant Reactions. Phase diagrams can be used in a manner similar to that used in the discussion of eutectic and eutectoid reactions to determine the microstructures expected to result from cooling an alloy through any of the other six types of reactions listed in Table 1.

Solid-State Precipitation. If alloy *X* in Fig. 21 is homogenized at a temperature between T_3 and T_5, it will reach equilibrium condition; that is, the portion of the eutectic constituent will dissolve and the microstructure will consist solely of grains. Upon cooling below temperature T_5, this microstructure will no longer represent equilibrium conditions, but instead will be supersaturated with B atoms. In order for the sample to return to equilibrium, some of the

B atoms will tend to congregate in various regions of the sample to form colonies of new material. The B atoms in some of these colonies, called *Guinier-Preston zones,* will drift apart, while other colonies will grow large enough to form incipient, but not distinct, particles. The difference in crystal structures and lattice parameters between the and phases causes lattice strain at the boundary between the two materials, thereby raising the total energy level of the sample and hardening and strengthening it. At this stage, the incipient particles are difficult to distinguish in the microstructure. Instead, there usually is only a general darkening of the structure. If sufficient time is allowed, the regions will break away from their host grains of and precipitate as distinct particles, thereby relieving the lattice strain and returning the hardness and strength to the former levels. While this process is illustrated for a simple eutectic system, it can occur wherever similar conditions exist in a phase diagram; that is, there is a range of alloy compositions in the system for which there is a transition on cooling from a single-solid region to a region that also contains a second solid phase, and where the boundary between the regions slopes away from the composition line as cooling continues. Several examples of such systems are shown schematically in Fig. 24.



Miscibility gap
$\alpha_0 \rightarrow \alpha_1 + \alpha_2$

Sloping solvus: decreasing solid solubility with decreasing temperature
$\alpha_0 \rightarrow \alpha + \beta$

Proeutectoid reaction
$\beta_0 \rightarrow \alpha + \beta$

Intermediate phase
$I_0 \rightarrow I + \alpha$

Promonotectoid; similar to miscibility gap
$\alpha_0 \rightarrow \alpha_1 + \alpha_2$

Heterogeneous ordering; γ is an ordered phase
$\alpha_0 \rightarrow \alpha + \gamma$

Fig. 24 Examples of binary phase diagrams that give rise to precipitation reactions. Source: Ref 6

Although this entire process is called *precipitation hardening,* the term normally refers only to the portion before much actual precipitation takes place. Because the process takes a while to be accomplished, the term *age hardening* is often used instead. The rate at which aging occurs depends on the level of supersaturation (how far from equilibrium), the amount of lattice strain originally developed (amount of lattice mismatch), the fraction left to be relieved (how far along the process has progressed), and the aging temperature (the mobility of the atoms to migrate). The precipitate usually takes the form of small idiomorphic particles situated along the grain boundaries and within the grains of phase. In most instances, the particles are more or less uniform in size and oriented in a systematic fashion. Examples of precipitation microstructures are shown in Fig. 25.

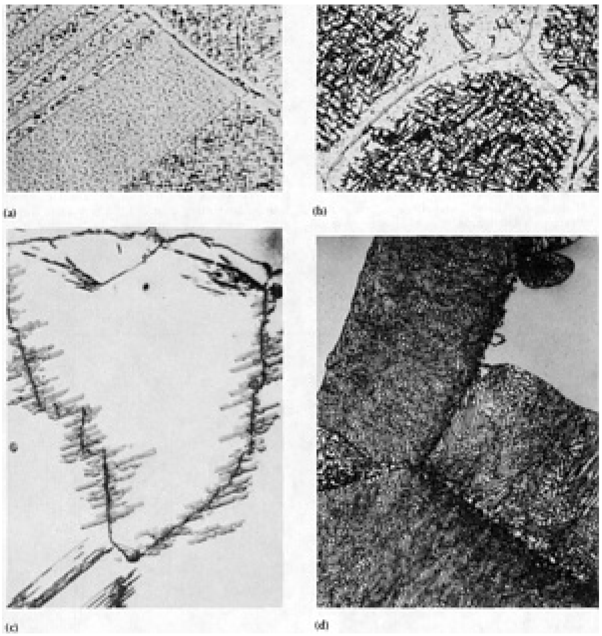


Fig. 25 Examples of characteristic precipitation microstructures. (a) General and grain-boundary precipitation of Co$_3$Ti (' phase) in a Co-12Fe-6Ti alloy aged 3 × 10^3 min at 800 °C (1470 °F). 1260×. (b) General precipitation (intragranular Widmanstätten), localized grain-boundary precipitation in Al-18Ag alloy aged 90 h at 375 °C (710 °F), with a distinct precipitation-free zone near the grain boundaries. 500×. (c) Preferential, or localized, precipitation along grain boundaries in a Ni-20Cr-1Al alloy. 500×. (d) Cellular, or discontinuous, precipitation growing out uniformly from the grain boundaries in an Fe-24.8Zn alloy aged 6 min at 600 °C (1110 °F). 1000×. Source: Ref 6

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Examples of Phase Diagrams

The general principles of reading alloy phase diagrams are discussed in the preceding section. The application of these principles to actual diagrams for typical alloy systems is illustrated below.

The Copper-Zinc System. The metallurgy of brass alloys has long been of great commercial importance. The copper and zinc contents of five of the most common wrought brasses are:

UNS No.	**Common name**	**Zinc content, %**	
		Nominal Range	**Range**
C23000	Red brass, 85%	15	14.0-16.0
C24000	Low brass, 80%	20	18.5-21.5
C26000	Cartridge brass, 70%	30	28.5-31.5
C27000	Yellow brass, 65%	35	32.5-37.0

As can be seen in Fig. 26, these alloys encompass a wide range of the copper-zinc phase diagram. The alloys on the high-copper end (red brass, low brass, and cartridge brass) lie within the copper solid-solution phase field and are called α brasses after the old designation for this field. As expected, the microstructure of these brasses consists solely of grains of copper solid solution (see Fig. 27a). The strain on the copper crystals caused by the presence of the zinc atoms, however, produces solution hardening in the alloys. As a result, the strength of the brasses, in both the work-hardened and the annealed condition, increases with increasing zinc content.

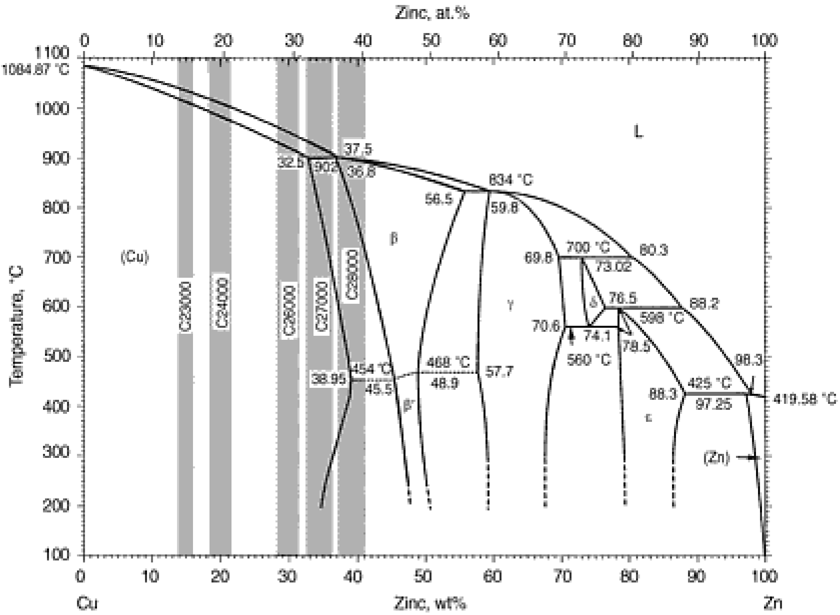


Fig. 26 The copper-zinc phase diagram, showing the composition range for five common brasses. Source: adapted from Ref 7

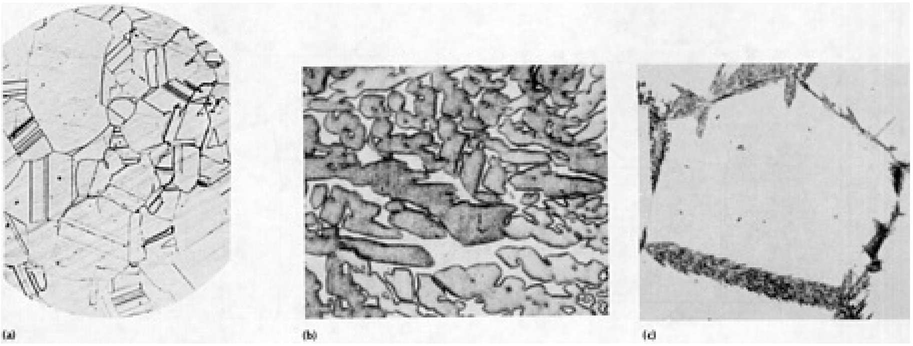


Fig. 27 The microstructure of two common brasses. (a) C26000 (cartridge brass, 70Cu-30Zn), hot rolled, annealed, cold rolled 70% and annealed at 638 °C (1180 °F), showing equiaxed grains of copper solid solution. (Some grains are twinned). 75×. (b) C28000 (Muntz metal, 60Cu-40Zn) ingot, showing dendrites of copper solid solution in a matrix of β. 200×. (c) C28000 (Muntz metal), showing feathers of copper solid solution, which formed at β grain boundaries during quenching of all-β structure. 100×. Source: Ref 6

The composition range for those brasses containing higher amounts of zinc (yellow brass and Muntz metal), however, overlaps into the two-phase (Cu)-plus-β field. Therefore, the microstructure of these so-called α-β alloys shows various amounts of βphase (see Fig. 27b and 27c), and their strengths are further increased over those of the αbrasses.

The Aluminum-Copper System. Another alloy system of great commercial importance is aluminum-copper. Although the phase diagram of this system is fairly complicated (see Fig. 28), the alloys of concern in this discussion are limited to the region at the aluminum side of the diagram where a simple eutectic is formed between the aluminum solid solution and the θ(Al_2Cu) phase. This family of alloys (designated the 2*xxx* series) has nominal copper contents ranging from 2.3 to 6.3 wt% Cu, making them hypoeutectic alloys.

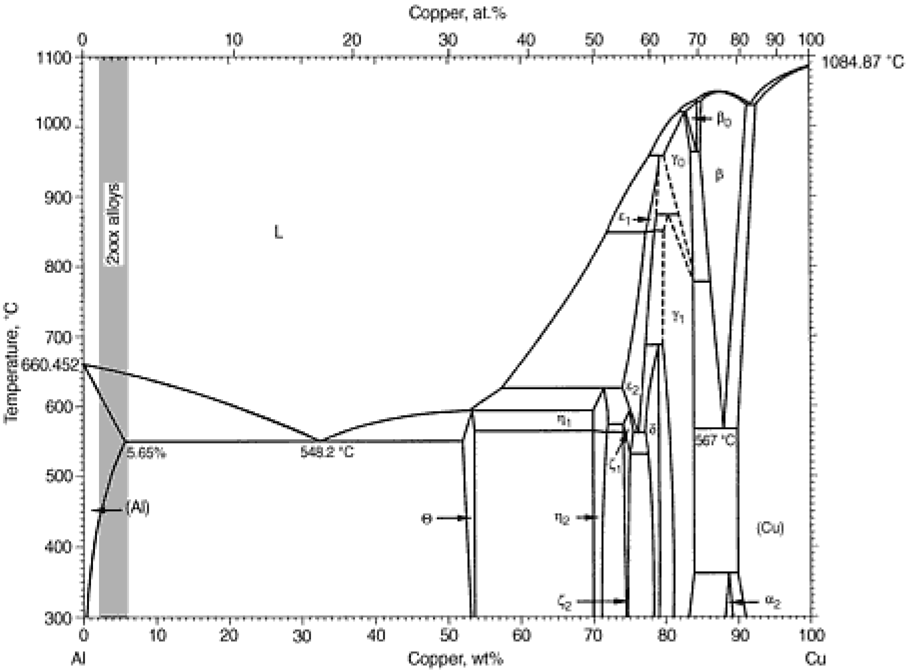


Fig. 28 The aluminum-copper phase diagram, showing the composition range for the 2*xxx* series of precipitation-hardenable aluminum alloys. Source: Ref 7

A critical feature of this region of the diagram is the shape of the aluminum solvus line. At the eutectic temperature (548.2 °C, or 1018.8 °F), 5.65 wt% Cu will dissolve in aluminum. At lower temperatures, however, the amount of copper that can remain in the aluminum solid solution under equilibrium conditions drastically decreases, reaching less than 1% at room temperature. This is the typical shape of the solvus line for precipitation hardening; if any of these alloys are homogenized at temperatures in or near the solid-solution phase field, they can be strengthened by aging at a substantially lower temperature.

The Aluminum-Magnesium System. As can be seen in Fig. 29, both ends of the aluminum-magnesium system have solvus lines that are shaped similarly to the aluminum solvus line in Fig. 28. Therefore, both aluminum-magnesium alloys and magnesium-aluminum alloys are age hardenable and commercially important.

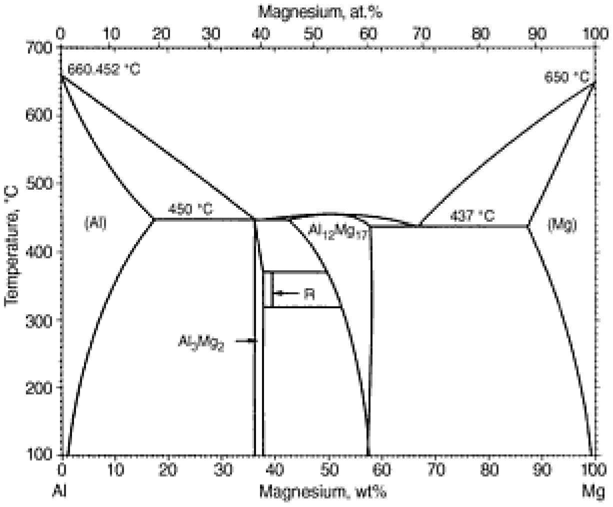


Fig. 29 The aluminum-magnesium phase diagram. Source: Ref 7

The Aluminum-Silicon System. Nonferrous alloy systems do not have to be age hardenable to be commercially important. For example, in the aluminum-silicon system (Fig. 30), almost no silicon will dissolve in solid aluminum. Therefore, as-cast hypereutectic aluminum alloy 392 (Al-19% Si) to which phosphorus was added in the melt contains large particles of silicon in a matrix of aluminum-silicon eutectic (see Fig. 20). Aluminum-silicon alloys have good castability (silicon improves castability and fluidity) and good corrosion and wear resistance (because of the hard primary silicon particles). Small additions of magnesium render some aluminum-silicon alloys age hardenable.

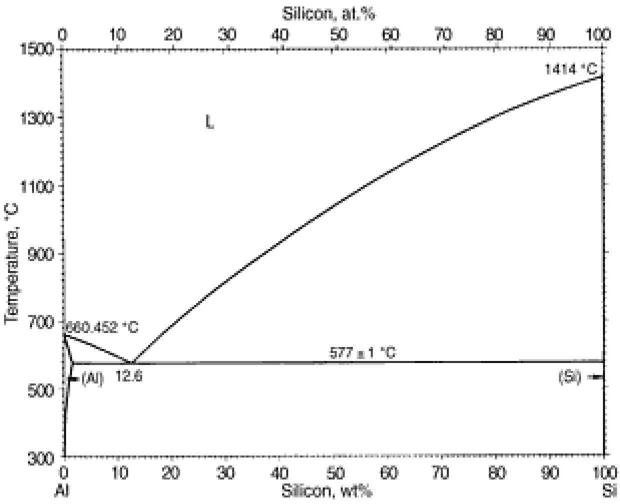


Fig. 30 The aluminum-silicon phase diagram. Source: Ref 7

The Lead-Tin System. The phase diagram of the lead-tin system (Fig. 31) shows the importance of the low-melting eutectic in this system to the success of lead-tin solders. While solders having tin contents between 18.3 to 61.9% all have the same freezing temperature (183 °C, or 361 °F), the freezing range (and the castability) of the alloys varies widely.

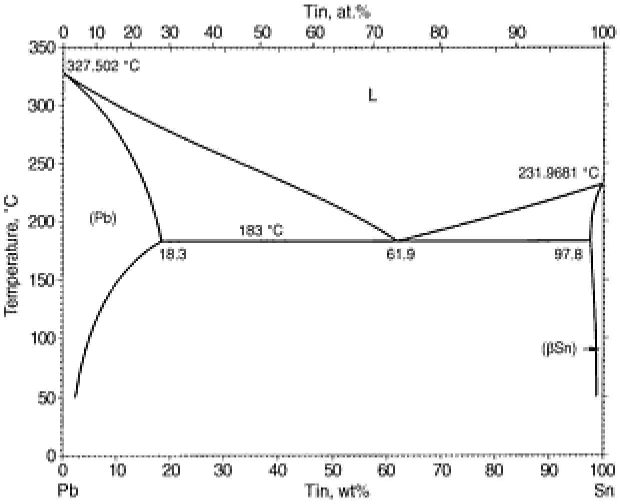


Fig. 31 The lead-tin phase diagram. Source: Ref 7

The Titanium-Aluminum and Titanium-Vanadium Systems. The phase diagrams of titanium systems are dominated by the fact that there are two allotropic forms of solid titanium: cph αTi is stable at room temperature and up to 882 °C (1620 °F); bcc βTi is stable from 882 °C to the melting temperature. Most alloying elements used in commercial titanium alloys can be classified as αstabilizer (such as aluminum) or βstabilizers (such as vanadium and chromium), depending on whether the allotropic transformation temperature is raised or lowered by the alloying addition (see Fig. 32). Beta stabilizers are further classified as those that are completely miscible with βTi (such as vanadium, molybdenum, tantalum, and niobium) and those that form eutectoid systems with titanium (such as chromium and iron). Tin and zirconium also are often alloyed in titanium, but instead of stabilizing either phase, they have extensive solubilities in both αTi and βTi. The microstructures of commercial titanium alloys are complicated because most contain more than one of these four types of alloying elements.

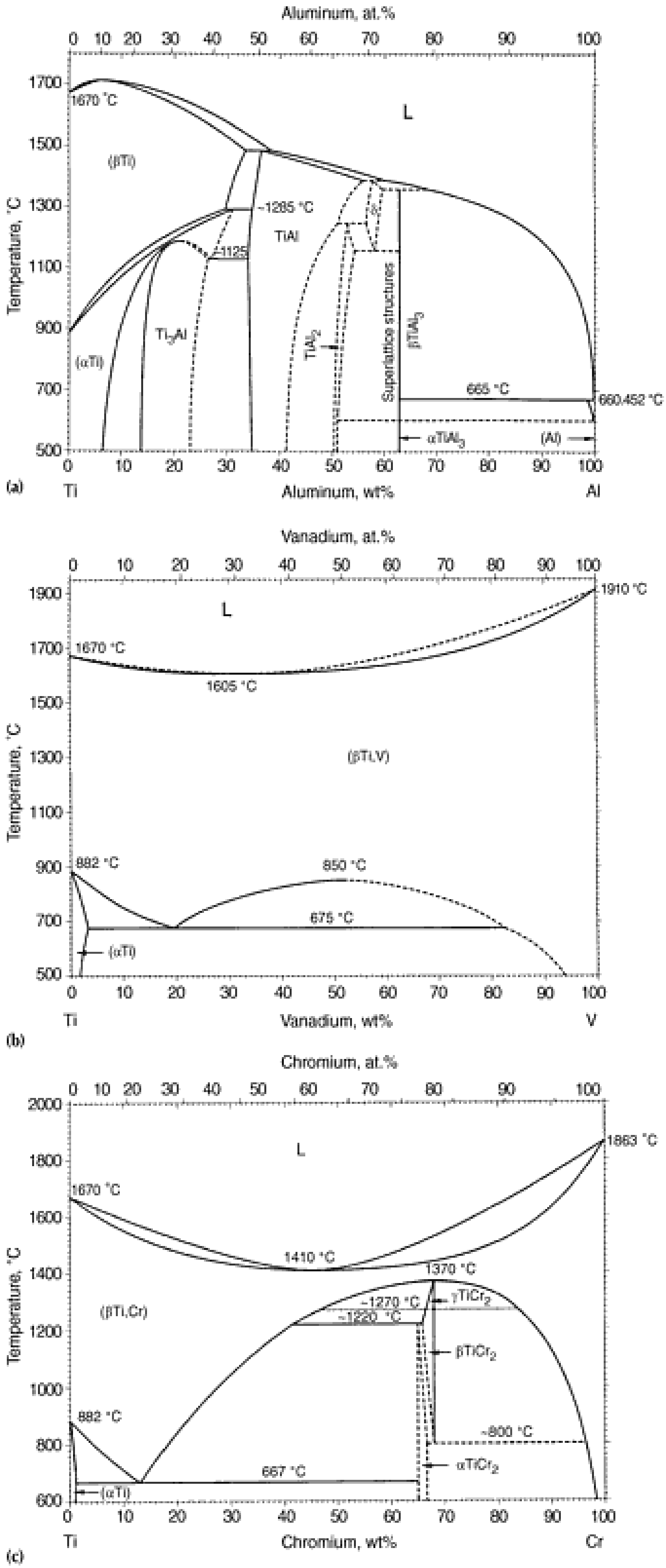


Fig. 32 Three representative binary titanium phase diagrams, showing (a) α stabilization (Ti-Al), (b) β stabilization with complete miscibility (Ti-V), and (c) β stabilization with a eutectoid reaction (Ti-Cr). Source: Ref 7

The Iron-Carbon System. The iron-carbon diagram maps out the stable equilibrium conditions between iron and the graphitic form of carbon (see Fig. 33). Note that there are three allotropic forms of solid iron: the low-temperature phase, α; the medium-temperature phase, γ; and the high-temperature phase, δ. In addition, ferritic iron undergoes a magnetic phase transition at 771 °C (1420 °F) between the low-temperature ferromagnetic state and the higher-temperature paramagnetic state. The common name for bcc Fe is "ferrite" (from *ferrum,* Latin for "iron"); the fcc γ phase is called "austenite" after William Roberts-Austen; bcc Fe also is commonly called ferrite because (except for its temperature range) it is the same as α-Fe. The main features of the iron-carbon diagram are the presence of both a eutectic and a eutectoid reaction, along with the great difference between the solid solubility of carbon in ferrite and austenite. It is these features that allow such a wide variety of microstructures and mechanical properties to be developed in iron-carbon alloys through proper heat treatment.

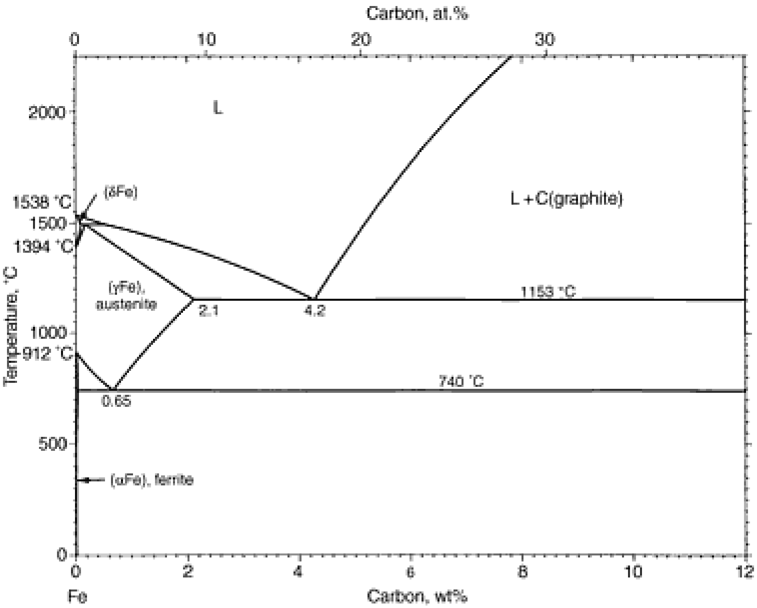


Fig. 33 The iron-carbon phase diagram. Source: Ref 7

The Iron-Cementite System. In the solidification of steels, stable equilibrium conditions do not exist. Instead, any carbon not dissolved in the iron is tied up in the form of the metastable intermetallic compound, Fe_3C (also called cementite because of its hardness), rather than remaining as free graphite (see Fig. 34). It is, therefore, the iron-cementite phase diagram, rather than the iron-carbon diagram, that is important to industrial metallurgy. It should be remembered, however, that while cementite is an extremely enduring phase, given sufficient time, or the presence of a catalyzing substance, it will break down to iron and carbon. In cast irons, silicon is the catalyzing agent that allows free carbon (flakes, nodules, etc.) to appear in the microstructure (see Fig. 35).

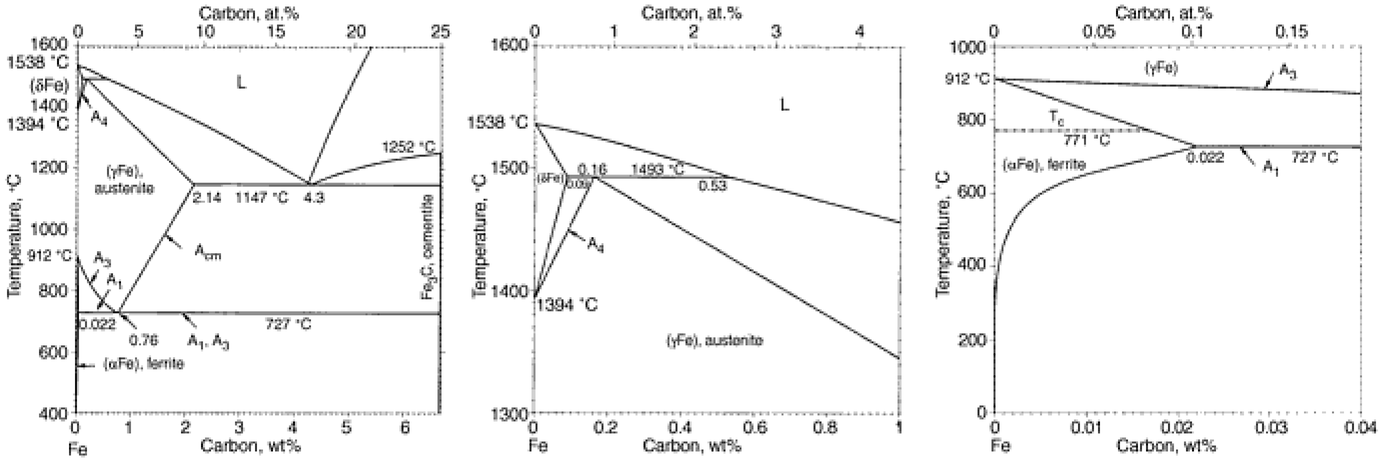


Fig. 34 The iron-cementite phase diagram and details of the (δFe) and (αFe) phase fields. Source: Ref 7

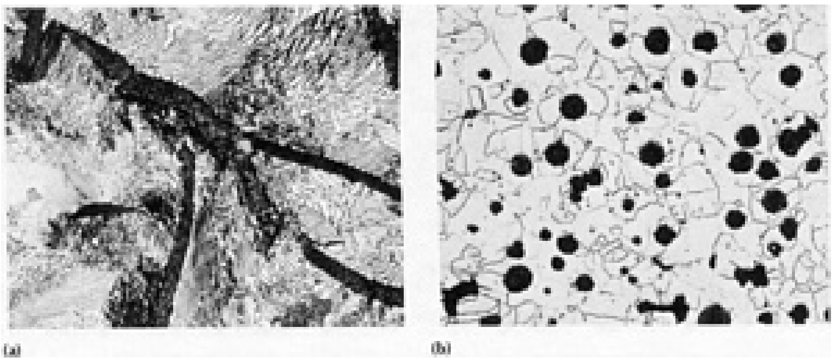


Fig. 35 The microstructure of two types of cast irons. (a) As-cast class 30 gray iron, showing type A graphite flakes in a matrix of pearlite. 500×. (b) As-cast grade 60-45-12 ductile iron, showing graphite nodules (produced by addition of calcium-silicon compound during pouring) in a ferrite matrix. 100×. Source: Ref 6

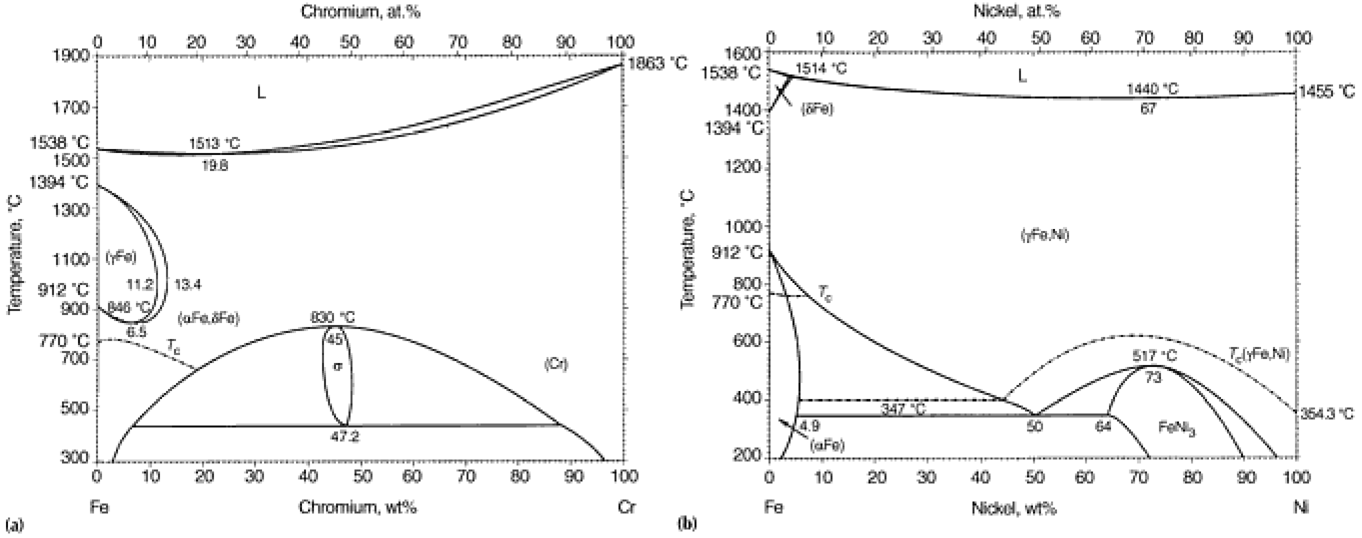
The boundary lines on the iron-carbon and iron-cementite diagrams that are important to the heat treatment of steel and cast iron have been assigned special designations, which have been found useful in describing the treatments. These lines, where thermal arrest takes place during heating or cooling due to a solid-state reaction, are assigned the letter "A" for *arrêt* (French for "arrest"). These designations are shown in Fig. 34. To further differentiate the lines, an "e" is added to identify those indicating the changes occurring at equilibrium (to give Ae_1, Ae_3, Ae_4, and Ae_{cm}). Also, because the temperatures at which changes actually occur on heating or cooling are displaced somewhat from the equilibrium values, the "e" is replaced with "c" (for *chauffage,* French for "heating") when identifying the slightly higher temperatures associated with changes that occur on heating. Likewise, "e" is replaced with "r" (for *refroidissement,* French for "cooling") when identifying those slightly lower temperatures associated with changes occurring on cooling. These designations are convenient terms because they are not only used for binary alloys of iron and carbon, but also for commercial steels and cast irons, regardless of the other elements present in them. Alloying elements such as manganese, chromium, nickel, and molybdenum, however, do affect these temperatures (mainly A_3). For example, nickel lowers A_3 whereas chromium raises it.

The microstructures obtained in steels by slowly cooling are as follows. At carbon contents from 0.007 to 0.022%, the microstructure consists of ferrite grains with cementite precipitated in from ferrite, usually in too fine a form to be visible by light microscopy. (Because certain other metal atoms that may be present can substitute for some of the iron atoms in Fe_3C, the more general term, "carbide," is often used instead of "cementite" when describing microstructures). In the hypoeutectoid range (from 0.022 to 0.76% C), ferrite and pearlite grains comprise the microstructure. In the hypereutectoid range (from 0.76 to 2.14% C), pearlite grains plus carbide precipitated from austenite are visible.

Slowly cooled hypoeutectic cast irons (from 2.14 to 4.3% C) have a microstructure consisting of dendritic pearlite grains (transformed from hypoeutectic primary austenite) and grains of iron-cementite eutectic (called "ledeburite" after Adolf Ledebur) consisting of carbide and transformed austenite, plus carbide precipitated from austenite and particles of free carbon. For slowly cooled hypereutectic cast iron (between 4.3 and 6.67% C), the microstructure shows primary particles of carbide and free carbon, plus grains of transformed austenite.

Cast irons and steels, of course, are not used in their slowly cooled as-cast condition. Instead, they are more rapidly cooled from the melt, then subjected to some kind of heat treatment and, for wrought steels, some kind of hot and/or cold work. The great variety of microconstituents and microstructures that result from these treatments is beyond the scope of a discussion of stable and metastable equilibrium phase diagrams. Phase diagrams are, however, invaluable when designing heat treatments. For example, normalizing is usually accomplished by air cooling from about 55 °C (100 °F) above the upper transformation temperature (A_3 for hypoeutectoid alloys and A_{cm} for hypereutectoid alloys). Full annealing is done by controlled cooling from about 28 to 42 °C (50 to 75 °F) above A_3 for both hypoeutectoid and hypereutectoid alloys. All tempering and process-annealing operations are done at temperatures below the lower transformation temperature (A_1). Austenitizing is done at a temperature sufficiently above A_3 and A_{cm} to ensure complete transformation to austenite, but low enough to prevent grain growth from being too rapid.

The Fe-Cr-Ni System. Many commercial cast irons and steels contain ferrite-stabilizing elements (such as silicon, chromium, molybdenum, and vanadium) and/or austenite stabilizers (such as manganese and nickel). The diagram for the binary iron-chromium system is representative of the effect of a ferrite stabilizer (see Fig. 36a). At temperatures just below the solidus, bcc chromium forms a continuous solid solution with bcc (δ) ferrite. At lower temperatures, the γ-Fe phase appears on the iron side of the diagram and forms a "loop" extending to about 11.2% Cr. Alloys containing up to 11.2% Cr, and sufficient carbon, are hardenable by quenching from temperatures within the loop.



Chromium, at.%
0
10
20
30
40
50
60
70
80
90
100
1900
1700
1538 °C
1500
1394 °C
1300
1100
912 °C
900
770 °C
700
500
300
Temperature, °C
1863 °C
L
1513 °C
19.8
(γFe)
11.2
13.4
846 °C
6.5
(αFe,δFe)
T_c
830 °C
45
σ
(Cr)
47.2
Fe
Chromium, wt%
Cr
(a)
Nickel, at.%
1600
1538 °C
1400
1394 °C
1200
1000
912 °C
800
770 °C
600
400
200
Temperature, °C
1514 °C
L
(δFe)
1440 °C
67
1455 °C
(γFe,Ni)
T_c
517 °C
73
T_c(γFe,Ni)
347 °C
354.3 °C
4.9
(αFe)
50
64
$FeNi_3$
Fe
Nickel, wt%
Ni
(b)

Fig. 36 Two representative binary iron phase diagrams, (a) showing ferrite stabilization (Fe-Cr) and (b) austenite stabilization (Fe-Ni). Source: Ref 7

At still lower temperatures, the bcc solid solution is again continuous bcc ferrite, but this time with α Fe. This continuous bcc phase field confirms that δferrite is the same as αferrite. The nonexistence of γ-Fe in Fe-Cr alloys having more than about 13% Cr, in the absence of carbon, is an important factor in both the hardenable and nonhardenable grades of iron-chromium stainless steels. Also at these lower temperatures, a material known as σ phase appears in different amounts from about 14 to 90% Cr. Sigma is a hard, brittle phase and usually should be avoided in commercial stainless steels. Formation of α, however, is time dependent; long periods at elevated temperatures are usually required.

The diagram for the binary iron-nickel system is representative of the effect of an austenite stabilizer (see Fig. 36b). The fcc nickel forms a continuous solid solution with fcc (γ) austenite that dominates the diagram, although the α ferrite phase field extends to about 6% Ni. The diagram for the ternary Fe-Cr-Ni system shows how the addition of ferrite-stabilizing chromium affects the iron-nickel system (see Fig. 37). As can be seen, the popular 18-8 stainless steel, which contains about 8% Ni, is an all-austenite alloy at 900 °C (1652 °F), even though it also contains about 18% Cr.

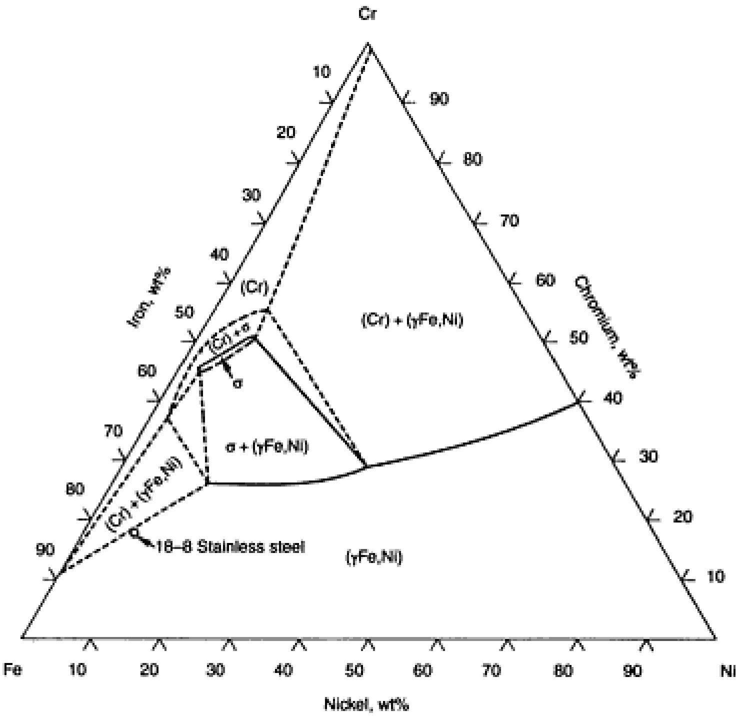

Cr
Iron, wt%
10
20
30
40
50
60
70
80
90
Chromium, wt%
90
80
70
60
50
40
30
20
10
Fe
10
20
30
40
50
60
70
80
90
Ni
Nickel, wt%
(Cr)
(Cr) + σ
σ
(Cr) + (γFe,Ni)
σ + (γFe,Ni)
(Cr) + (γFe,Ni)
18–8 Stainless steel
(γFe,Ni)

Fig. 37 The isothermal section at 900 °C (1652 °F) of the Fe-Cr-Ni ternary phase diagram, showing the nominal composition of 18-8 stainless steel. Source: Ref 8

The Cr-Mo-Ni System. In addition to its use in alloy and stainless steels and in cobalt- and copper-base alloys, nickel is also used as the basis of a family of alloys. Many of these nickel-base alloys are alloyed with chromium and molybdenum (and other elements) to improve corrosion and heat resistance. As the chromium and the molybdenum contents in most commercial Ni-Cr-Mo alloys range from 0 to about 30%, the phase diagram shown in Fig. 38 indicates that their microstructures normally consist of a matrix of γ solid solution, although this matrix is usually strengthened by a dispersion of second-phase materials such as carbides. For example, precipitated fcc γ' (Ni_3Al,Ti) improves high-temperature strength and creep resistance.

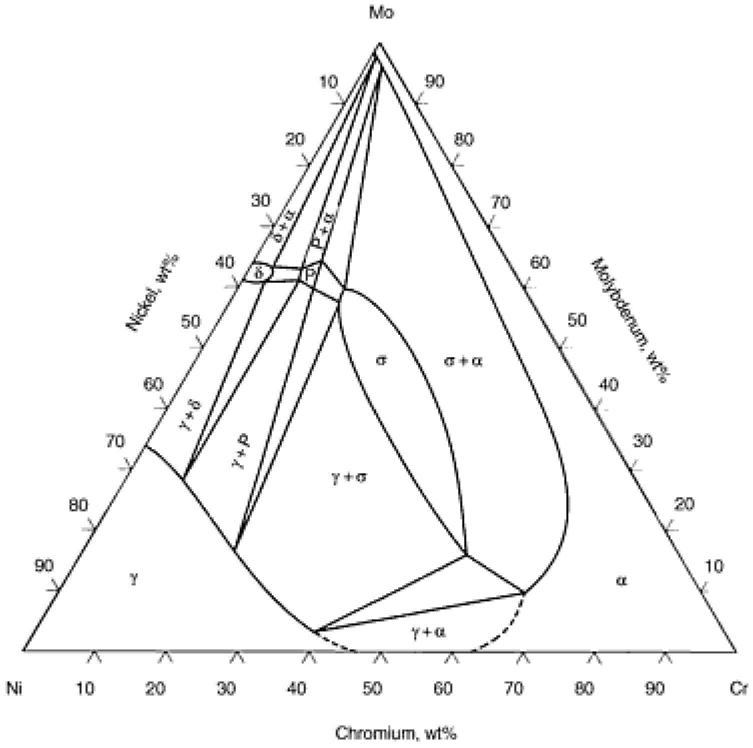

Mo
Nickel, wt%
Molybdenum, wt%
Chromium, wt%
Ni
Cr
10
20
30
40
50
60
70
80
90
δ+α
P+α
δ
P
σ
σ+α
γ+δ
γ+P
γ+σ
γ
α
γ+α

Fig. 38 The isothermal section at 1250 °C (2280 °F) of the Cr-Mo-Ni nickel ternary phase diagram. Source: Ref 9

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Appendix 1

Melting and boiling points of the elements at atmospheric pressure

Symbol	**Melting point**			**Boiling point**	
	°C	**°K**	**Error limits**	**°C**	**°K**
Ac	1051	1324	±50	3200	3473[(a)]
Ag	961.93	1235.08	. . .	2163	2436
Al	660.452	933.602	. . .	2520	2793
Am	1176	1449	. . .	. . .	. . .

Ar	-189.352(T.P.)	83.798(T.P.)	. . .	-185.9	87.3
As	614(S.P.)	887(S.P.)	. . .	. . .	. . .
At	(302)	(575)	. . .	. . .	. . .
Au	1064.43	1337.58	. . .	2857	3130
B	2092	2365	. . .	4002	4275
Ba	727	1000	±2	1898	2171
Be	1289	1562	±5	2472	2745
Bi	271.442	544.592	. . .	1564	1837
Bk	1050	1323	. . .	. . .	. . .
Br	-7.25(T.P.)	265.90(T.P.)	. . .	59.10	332.25
C	3827(S.P.)	4100(S.P.)	±50	. . .	. . .
Ca	842	1115	±2	1484	1757
Cd	321.108	594.258	. . .	767	1040
Ce	798	1071	±3	3426	3699
Cf	900	1173	. . .	. . .	. . .
Cl	-100.97(T.P.)	172.18(T.P.)	. . .	-34.05	239.10
Cm	1345	1618	. . .	. . .	. . .
Co	1495	1768	. . .	2928	3201
Cr	1863	2136	±20	2672	2945
Cs	28.39	301.54	±0.05	671	944
Cu	1084.87	1358.02	±0.04	2563	2836

Dy	1412	1685	. . .	2562	2835
Er	1529	1802	. . .	2863	3136
Es	860	1133	. . .	. . .	. . .
Eu	822	1095	. . .	1597	1870
F	-219.67(T.P.)	53.48(T.P.)	. . .	-188.20	84.95
Fe	1538	1811	. . .	2862	3135
Fm	(1527)	(1800)	. . .	. . .	. . .
Fr	(27)	(300)	. . .	. . .	. . .
Ga	29.7741(T.P.)	302.9241(T.P.)	±0.001	2205	2478
Gd	1313	1586	. . .	3266	3539
Ge	938.3	1211.5	. . .	2834	3107
H	-259.34(T.P.)	13.81(T.P.)	. . .	-252.882	20.268
He	-271.69(T.P.)	1.46(T.P.)	(b)	-268.935	4.215
Hf	2231	2504	±20	4603	4876
Hg	-38.836	234.210	. . .	356.623	629.773
Ho	1474	1747	. . .	2695	2968
I	113.6	386.8	. . .	185.25	458.40
In	156.634	429.784	. . .	2073	2346
Ir	2447	2720	. . .	4428	4701
K	63.71	336.86	±0.5	759	1032
Kr	-157.385	115.765	±0.001	-153.35	119.80

La	918	1191	. . .	3457	3730
Li	180.6	453.8	±0.5	1342	1615
Lr	(1627)	(1900)	. . .	. . .	. . .
Lu	1663	1936	. . .	3395	3668
Md	(827)	(1100)	. . .	. . .	. . .
Mg	650	923	±0.5	1090	1363
Mn	1246	1519	±5	2062	2335
Mo	2623	2896	. . .	4639	4912
N	-210.0042(T.P.)	63.1458(T.P.)	±0.0002	-195.80	77.35
Na	97.8	371.0	±0.1	883	1156
Nb	2469	2742	. . .	4744	5017
Nd	1021	1294	. . .	3068	3341
Ne	-248.587(T.P.)	24.563(T.P.)	±0.002	-246.054	27.096
Ni	1455	1728	. . .	2914	3187
No	(827)	(1100)	. . .	. . .	. . .
Np	639	912	±2	. . .	. . .
O	-218.789(T.P.)	54.361(T.P.)	. . .	-182.97	90.18
Os	3033	3306	±20	5012	5285
P(white)	44.14	317.29	±0.1	277	550
P(red)	589.6(T.P.)	862.8(T.P.)	(c)	431	704
Pa	1572	1845	. . .	. . .	. . .

Pb	327.502	600.652	. . .	1750	2023
Pd	1555	1828	±0.4	2964	3237
Pm	102	1315	. . .	. . .	. . .
Po	254	527	. . .	. . .	. . .
Pr	931	1204	. . .	3512	3785
Pt	1769.0	2042.2	. . .	3827	4100
Pu	640	913	±1	3230	3503
Ra	700	973	. . .	. . .	. . .
Rb	39.48	312.63	±0.5	688	961
Re	3186	3459	±20	5596	5869
Rh	1963	2236	. . .	3697	3970
Rn	-71	202	. . .	-62	211
Ru	2334	2607	±10	4150	4423
S	115.22	388.37	. . .	444.60	717.75
Sb	630.755	903.905	. . .	1587	1860
Sc	1541	1814	. . .	2831	3104
Se	221	494	. . .	685	958
Si	1414	1687	±2	3267	3540
Sm	1074	1347	. . .	1791	2064
Sn	231.9681	505.1181	. . .	2603	2876
Sr	769	1042	. . .	1382	1655

Ta	3020	3293	. . .	5458	5731
Tb	1356	1629	. . .	3223	3496
Tc	2155	2428	±50	4265	4538
Te	449.57	722.72	±0.3	988	1261
Th	1755	2028	±10	4788	5061
Ti	1670	1943	±6	3289	3562
Tl	304	577	±2	1473	1746
Tm	1545	1818	. . .	1947	2220
U	1135	1408	. . .	4134	4407
V	1910	2183	±6	3409	3682
W	3422	3695	. . .	5555	5828
Xe	-111.7582 (T.P.)	161.3918 (T.P.)	±0.0002	-108.12	165.03
Y	1522	1795	. . .	3338	3611
Yb	819	1092	. . .	1194	1467
Zn	419.58	692.73	. . .	907	1180
Zr	1855	2128	±5	4409	4682

Note: T.P., triple point. S.P., sublimation point at atmospheric pressure. Measurements in parenthesis are approximate.

(a) ±300.

(b) There are various triple points.

(c) Red P sublimes without melting at atmosphere pressure.

Appendix 2

Allotropic transformations of the elements at atmospheric pressure

Element	Transformation	Temperature, °C
Ag	$L \leftrightarrow S$	0961.93
Al	$L \leftrightarrow S$	660.452
Am	$L \leftrightarrow \gamma$	1176
	$\gamma \leftrightarrow \beta$	1077
	$\beta \leftrightarrow \alpha$	769
Ar	$L \leftrightarrow S$	83.798K
Au	$L \leftrightarrow S$	1064.43
B	$L \leftrightarrow \beta$	2092
Ba	$L \leftrightarrow S$	727
Be	$L \leftrightarrow \beta$	1289
	$\beta \leftrightarrow \alpha$	1270
Bi	$L \leftrightarrow S$	271.442
Bk	$L \leftrightarrow S$	1050
Br	$L \leftrightarrow S$	265.9K
Ca	$L \leftrightarrow \beta$	842
	$\beta \leftrightarrow \alpha$	443
Cd	$L \leftrightarrow S$	321.108

Ce	L $\leftrightarrow \delta$	798
	$\delta \leftrightarrow \gamma$	726
	$\gamma \leftrightarrow \beta$	61
	$\beta \leftrightarrow \alpha$	. . .
Cf	L $\leftrightarrow \beta$	900
	$\beta \leftrightarrow \alpha$	590
Cl	L $\leftrightarrow$ S	172.16K
Cm	L $\leftrightarrow \beta$	1345
	$\beta \leftrightarrow \gamma$	1277
Co	L $\leftrightarrow \alpha$	1495
	$\alpha \leftrightarrow \varepsilon$	422
Cr	L $\leftrightarrow$ S	1863
Cs	L $\leftrightarrow$ S	28.39
Cu	L $\leftrightarrow$ S	1084.87
Dy	L $\leftrightarrow \beta$	1412
	$\beta \leftrightarrow \alpha$	1381
	$\alpha \leftrightarrow \alpha'$	-187
Er	L $\leftrightarrow$ S	1529
Es	L $\leftrightarrow$ S	860

Eu	L $\leftrightarrow$ S	822
F	L $\leftrightarrow\beta$	53.48K
	$\beta\leftrightarrow\alpha$	45.55K
Fe	L $\leftrightarrow\delta$	1538
	$\delta\leftrightarrow\gamma$	1394
	$\gamma\leftrightarrow\alpha$	912
Ga	L $\leftrightarrow$ S	29.7741
Gd	L $\leftrightarrow\beta$	1313
	$\beta\leftrightarrow\alpha$	1235
Ge	L $\leftrightarrow$ S	938.3
H	L $\leftrightarrow$ S	13.81K
Hf	L $\leftrightarrow\beta$	2231
	$\beta\leftrightarrow\alpha$	1743
Hg	L $\leftrightarrow\alpha$	-38.290
Ho	L $\leftrightarrow$ S	1474
I	L $\leftrightarrow$ S	113.6
In	L $\leftrightarrow$ S	156.634
Ir	L $\leftrightarrow$ S	2447
K	L $\leftrightarrow$ S	63.71
Kr	L $\leftrightarrow$ S	115.65K

La	L $\leftrightarrow\gamma$	918
	$\gamma\leftrightarrow\beta$	865
	$\beta\leftrightarrow\alpha$	310
Li	L $\leftrightarrow\beta$	180.6
	$\beta\leftrightarrow\alpha$	-193
Lu	L $\leftrightarrow$S	1663
Mg	L $\leftrightarrow$S	650
Mn	L $\leftrightarrow\delta$	1246
	$\delta\leftrightarrow\gamma$	1138
	$\gamma\leftrightarrow\beta$	1100
	$\beta\leftrightarrow\alpha$	727
Mo	L $\leftrightarrow$S	2623
N	L $\leftrightarrow\beta$	63146K
	$\beta\leftrightarrow\alpha$	35.61K
Na	L $\leftrightarrow\beta$	97.8
	$\beta\leftrightarrow\alpha$	-233
Nb	L $\leftrightarrow$S	2469
Nd	L $\leftrightarrow\beta$	1021
	$\beta\leftrightarrow\alpha$	863

Ne	L $\leftrightarrow$S	24.563K(T.P.)
Ni	L $\leftrightarrow$S	1455
Np	L $\leftrightarrow\gamma$	639
	$\gamma\leftrightarrow\beta$	576
	$\beta\leftrightarrow\alpha$	280
O	L $\leftrightarrow\gamma$	54.361K
	$\gamma\leftrightarrow\beta$	43.801K
	$\beta\leftrightarrow\alpha$	23.867K
Os	L $\leftrightarrow$S	3033
P(white α)	L $\leftrightarrow\alpha$	44.14
Pa	L $\leftrightarrow\beta$	1572
	$\beta\leftrightarrow\alpha$	1170
Pb	L $\leftrightarrow$S	327.502
Pd	L $\leftrightarrow$S	1555
Pm	L $\leftrightarrow\beta$	1042
	$\beta\leftrightarrow\alpha$	890
Po	L $\leftrightarrow\beta$	254
	$\beta\leftrightarrow\alpha$	54
Pr	L $\leftrightarrow\beta$	931

	$\beta \leftrightarrow \alpha$	795
Pt	L ↔ S	1769.0
Pu	L ↔ ε	640
	$\varepsilon \leftrightarrow \delta'$	483
	$\delta' \leftrightarrow \delta$	463
	$\delta \leftrightarrow \gamma$	320
	$\gamma \leftrightarrow \beta$	215
	$\beta \leftrightarrow \alpha$	125
Rb	L ↔ S	39.48
Re	L ↔ S	3186
Rh	L ↔ S	1963
Rn	L ↔ S	-71
Ru	L ↔ S	2334
S	L ↔ β	115.22
	$\beta \leftrightarrow \alpha$	95.5
Sb	L ↔ S	630.755
Sc	L ↔ β	1541
	$\beta \leftrightarrow \alpha$	1337
Se	L ↔ S	221
Si	L ↔ S	1414

Sm	$L \leftrightarrow \beta$	1074
	$\gamma \leftrightarrow \beta$	922
	$\beta \leftrightarrow \alpha$	734
Sn	$L \leftrightarrow \beta$	231.9681
	$\beta \leftrightarrow \alpha$	13
Sr	$L \leftrightarrow \beta$	769
	$\beta \leftrightarrow \alpha$	547
Ta	$L \leftrightarrow S$	3020
Tb	$L \leftrightarrow \beta$	1356
	$\beta \leftrightarrow \alpha$	1289
	$\alpha \leftrightarrow \alpha'$	-53
Te	$L \leftrightarrow S$	449.57
Th	$L \leftrightarrow \beta$	1755
	$\beta \leftrightarrow \alpha$	1360
Ti	$L \leftrightarrow \beta$	1670
	$\beta \leftrightarrow \alpha$	882
Tl	$L \leftrightarrow \beta$	304
	$\beta \leftrightarrow \alpha$	230
Tm	$L \leftrightarrow S$	1545

U	$L \leftrightarrow \gamma$	1135
	$\gamma \leftrightarrow \beta$	776
	$\beta \leftrightarrow \alpha$	668
V	$L \leftrightarrow S$	1910
W	$L \leftrightarrow S$	3422
Xe	$L \leftrightarrow S$	161.918(T.P.)
Y	$L \leftrightarrow \beta$	1522
	$\beta \leftrightarrow \alpha$	1478
Yb	$L \leftrightarrow \gamma$	819
	$\gamma \leftrightarrow \beta$	795
	$\beta \leftrightarrow \alpha$	-3
Zn	$L \leftrightarrow S$	419.58
Zr	$L \leftrightarrow \beta$	1855
	$\beta \leftrightarrow \alpha$	863

Note: T.P., triple point

Properties of Metals

Hugh Baker, Consulting Editor, ASM International

Introduction

THE PROPERTIES of materials determine their usefulness. In the context in which it is frequently used, the term "property" connotes something that a material inherently possesses. More properly, a property should be regarded as the response of a material to a given set of imposed conditions (e.g., temperature and/or pressure). Material properties are the link between the basic structure and composition of the material and the service performance of a part or component.

A wide variety of properties must be considered when choosing a material and a combination of properties is usually required for a given application. The properties of greatest importance for metals include:

- Physical properties, such as mass characteristics, thermal, electrical, magnetic, and optical properties
- Chemical properties, such as corrosion and oxidation resistance
- Mechanical properties, such as tensile and yield strength, elongation (ductility), toughness, and hardness

Many of these are discussed in this article. More detailed information can be found in the extensive data compilation on pure metals presented in Volume 2 of the *ASM Handbook.*

Physical Properties of Metals

Mass Characteristics

Mass characteristics include atomic weight and density. The *atomic weight* (or *relative atomic mass*) is the ratio of the average mass per atom of an element to $\frac{1}{12}$ of the mass of the atom of the nuclide ^{12}C. Atomic weights of the metallic elements are given in the periodic table in the introductory article in this Section entitled "The Chemical Elements." The term *density* refers to the mass per unit volume of a solid material and is usually expressed in g/cm^3 and abbreviated by the Greek letter rho, ρ. For solid materials, density decreases with increasing temperature. Examples of room-temperature density values for various metals can be found in Table 1.

Table 1 Some physical properties of metals at room temperature

Metal	**Density ρ_d, g/cm^3**	**Specific heat capacity (C_p), kJ/kg · K**	**Coefficient of linear thermal expansion (α), μm/m · K**	**Thermal conductivity (k), W/m · K**	**Electrical resistivity (ρ), nΩ · m**
Aluminum	2.6989	0.900	22.8	247	26.2
Antimony	6.697	0.207	8.5 to 10.8	25.9	370
Arsenic	5.778	0.328	5.6	. . .	260
Barium	3.5	0.26	18	18.4	600
Beryllium	1.848	1.886	9	210	40

Bismuth	9.808	0.122	13.2	8.2	1050
Boron	2.45	1.29	8.3	27.4	18 × 10^{12}
Cadmium	8.642	0.230	31.3	97.5	68.3
Calcium	1.55	0.6315	22.15	196	31.7
Carbon (graphite)(a)	2.25	0.691	0.6-4.3	23.9	13,750
Cerium	8.16	0.192	6.3	11.3	744
Cesium	1.903	0.2016	280	18.42	200
Chromium	7.19	0.4598	6.2	67	130
Cobalt	8.832	0.414	13.8	69.04	52.5
Copper	8.93	0.3846	16.5	398	16.730
Dysprosium	8.551	0.1705	9.9	10.7	926
Erbium	9.066	0.1680	12.2	14.5	860
Europium	5.244	0.1823	35.0	13.9	900
Gadolinium	7.901	0.2359	9.4	10.5	1310
Gallium	5.907	0.3738	18	33.49	150.5
Germanium	5.323	0.3217	5.722	58.6	530 × 10^{6}
Gold	19.302	0.128	14.2	317.9	23.5
Hafnium	13.31	0.147	519	23	351
Holmium	8.795	0.1649	11.2	16.2	814
Indium	7.30	0.233	24.8	83.7	84
Iridium	22.65	0.130	6.8	147	53

Iron	7.870	0.4473	11.8	80.4	97.1
Lanthanum	6.146	0.1951	12.1	13.4	615
Lead	11.34	0.1287	26.5	33.6	206.43
Lithium	0.5334	3.3054	56	44.0	93.5
Lutetium	9.841	0.1503	9.9	16.4	582
Magnesium	1.738	1.025	25.2	155	44.5
Manganese	7.43	0.475	21.7	7.79	1440
Mercury	13.546	0.1396	60.7	8.21	958
Molybdenum	10.22	0.276	5	142	52
Neodymium	7.008	0.1900	9.6	16.5	643
Nickel	8.902	0.471	13.3	82.9	68.44
Niobium	8.57	0.27	7.1	52.3	146
Osmium	22.58	0.12973	4.6	. . .	95
Palladium	12.02	0.245	11.76	70	108
Phosphorus (white)	1.83	0.741	125	0.236	10×10^7
Platinum	21.45	0.132	9.1	71.1	106
Plutonium	19.86	0.142	67	6.5	141.4
Potassium	0.855	0.770	83	108.3	72
Praseodymium	6.773	0.1946	6.7	12.5	700
Promethium	7.264	0.188	11(b)	15(b)	750(b)
Protactinium	15.43	. . .	9.9	47(b)	150

Rhenium	21.02	0.138	6.6	71.2	193
Rhodium	12.41	0.247	8.3	150	45.1
Rubidium	1.532	0.33489	90	58.3	115.4
Ruthenium	12.45	0.240	5.05	. . .	76
Samarium	7.520	0.1962	12.7	13.3	940
Scandium	2.989	0.5674	10.2	15.8	562
Selenium	4.809	0.317	49	2.48	100
Silicon	2.3290	0.713	2.616	156	1×10^6
Silver	10.49	0.235	19.0	428	14.7
Sodium	0.9674	1.2220	68.93	131.4	47.7
Strontium	2.6	0.176	. . .	. . .	. . .
Tantalum	16.6	0.1391	6.5	54.4	135.0
Technetium	11.5	. . .	7.05	50.2	185.0
Tellurium	6.237	0.201	18.2	5.98-6.02	1-50
Terbium	8.230	0.1818	10.3	11.1	1150
Thallium	11.872	0.130	28	47	150
Thorium	11.8	0.11308	10.9	77	157
Thulium	9.321	0.1598	13.3	16.9	676
Tin	5.765	0.205	21	62.8	110
Titanium	4.507	0.5223	8.41	11.4	420
Tungsten	19.254	0.128	3.01-8.87	160	53

Uranium	19.05	0.117	12	27.6	300
Vanadium	6.16	0.498	8.3	31.0	248
Ytterbium	6.903	0.1543	26.3	38.5	250
Yttrium	4.469	0.2981	10.6	17.2	596
Zinc	7.133	0.382	39.7	113	59.16
Zirconium	6.505	0.30	5.85	21.1	450

(a) The electrical resistivity of carbon in diamond form is > 107 nΩ · m.

Thermal Properties

Melting and Boiling Points. The *melting point* is the temperature at which the solid and liquid phases of a pure material are in equilibrium. The *boiling point* is the temperature at which the vapor pressure of a liquid equals the pressure of the surroundings: normally this pressure is taken to be 1 atm (760 torr). The melting and boiling points of the chemical elements and the temperatures at which allotropic phase transformations occur are given in Appendices 1 and 2 in the article "Alloy Phase Diagrams and Microstructure" in this Section.

Vapor Pressure. The *vapor pressure* of an element at a given temperature is related to the ratio of that temperature on the absolute scale to the boiling point of the element, also on the absolute scale. Vapor pressure values for various elements can be found in Table 2.

Table 2 Vapor pressures of the elements up to 1 atm (760 mm Hg)

Element	**Pressure, atm**											
	0.0001		**0.001**		**0.01**		**0.1**		**0.5**		**1.0**	
	°C	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**
Aluminum	1110	2030	1263	2305	1461	2662	1713	3115	1940	3524	2056	3733
Antimony	759	1398	872	1602	1013	1855	1196	2185	1359	2478	1440	2624
Arsenic	308	586	363	685	428	802	499	930	578	1072	610	1130
Bismuth	914	1677	1008	1846	1121	2050	1254	2289	1367	2493	1420	2588
Cadmium	307(a)	585(a)	384(b)	723(b)	471	880	594	1101	708	1306	765	1409

Calcium	688	1270	802(c)	1476(c)	958(b)	1756(b)	1175	2147	1380	2516	1487	2709
Carbon	3257	5895	3547	6417	3897	7047	4317	7803	4667	8433	4827	8721
Chromium	1420(a)	2588(a)	1594(b)	2901(b)	1813	3295	2097	3807	2351	4264	2482	4500
Copper	1412	2574	1602	2916	1844	3351	2162	3924	2450	4442	2595	4703
Gallium	1178	2152	1329	2424	1515	2759	1751	3184	1965	3569	2071	3760
Gold	1623	2953	1839	3342	2115	3839	2469	4476	2796	5065	2966	5371
Iron	1564	2847	1760	3200	2004	3639	2316	4201	2595	4703	2735	4955
Lead	815	1499	953	1747	1135	2075	1384	2523	1622	2952	1744	3171
Lithium	592	1098	707	1305	858	1576	1064	1947	1266	2311	1372	2502
Magnesium	516	961	608(a)	1126(a)	725(b)	1337(b)	886	1627	1030	1886	1107	2025
Manganese	1115(d)	2039(d)	1269(b)	2316(b)	1476	2889	1750	3182	2019	3666	2151	3904
Mercury	77.9(b)	172.2(b)	120.8	249.4	176.1	349.0	251.3	484.3	321.5	610.7	357	675
Molybdenum	2727	4941	3057	5535	3477	6291	4027	7281	4537	8199	4804	8679
Nickel	1586	2887	1782	3240	2025	3677	2321	4210	2593	4699	2732	4950
Platinum	2367	4293	2687	4869	3087	5589	3637	6579	4147	7497	4407	7965
Potassium	261	502	332	630	429	804	565	1051	704	1299	774	1425
Rubidium	223	433	288	550	377	711	497	927	617	1143	679	1254
Selenium	282	540	347	657	430	806	540	1004	634	1173	680	1256
Silicon	1572	2862	1707	3105	1867	3393	2057	3735	2217	4023	2287	4149
Silver	1169	2136	1334	2433	1543	2809	1825	3317	2081	3778	2212	4014
Sodium	349	660	429	804	534	993	679	1254	819	1506	892	1638

Strontium	. . .	. . .	(a)	(a)	877(b)	1629(b)	1081	1978	1279	2334	1384	2523
Tellurium	(a)	(a)	509(b)	948(b)	632	1170	810	1490	991	1816	1087	1989
Thallium	692	1277	809	1488	962	1764	1166	2131	1359	2478	1457	2655
Tin	. . .	. . .	. . .	. . .	. . .	. . .	1932(b)	3510(b)	2163	3925	2270	4118
Tungsten	3547	6417	3937	7119	4437	8019	5077	9171	5647	10197	5927	10701
Zinc	399(a)	750(a)	477(b)	891(b)	579	1074	717	1323	842	1548	907	1665

Source: K.K. Kelley, *Bur. Mines Bull.,* Vol 383, 1935

(a) In the solid state.

(b) In the liquid state.

(c) β.

(d) γ.

Thermal Expansion. Most solid materials expand upon heating and contract when cooled. The change in length with temperature for a solid material can be expressed as follows:

$$(l_f - l_o)/l_o = \alpha_1(T_f - T_o)$$

or

$$\Delta l/l_o = \alpha_1 \Delta T$$

where l_o and l_f represent, respectively, the original and final lengths with the temperature change from T_o to T_f. The parameter α_1 is called the *linear coefficient of thermal expansion* (CTE); it is a material property that is indicative of the extent to which a material expands upon heating and has units of reciprocal temperature (K^{-1}) or μm/m · K. Table 1 lists room-temperature linear CTE values for various metals. With respect to temperature, the magnitude of the CTE increases with rising temperature. In general, CTE values for metals fall between those of ceramics (lower values) and polymers (higher values).

Of course, heating or cooling affects all the dimensions of a body, with a resultant change in volume. Volume changes may be determined from:

$$\Delta V/V_o = \alpha_v \Delta T$$

where ΔV and V_o are the volume change and original volume, respectively, and α_v represents the volume coefficient of thermal expansion. In many materials, the value of α_v is anisotropic; that is, it depends on the crystallographic direction along which it is measured. For materials in which the thermal expansion is isotropic, α_v is approximately $3\alpha_1$.

Heat Capacity. A solid material, when heated, experiences an increase in temperature indicating that some energy has been absorbed. *Heat capacity* is the property that represents the ability of a material to absorb heat from external surroundings; it is the amount of energy required to produce a unit temperature rise. Heat capacity, C, is expressed as follows:

$$C = dQ/dT$$

where dQ is the energy required to produce a dT temperature change. Heat capacity is ordinarily specified per mole of material (e.g., J/mol · K). For most practical purposes the quantity used is the *specific heat capacity,* or *specific heat,* which is the quantity of heat required to change by one degree the temperature of a body of material of unit mass, expressed as J/kg · K. Lower and higher specific heat values correspond with lower and higher temperatures, respectively.

There are really two ways in which the specific heat can be measured according to the environmental conditions accompanying the transfer of heat. One is the specific heat capacity while maintaining the specimen volume constant, C_v; the other is for constant external pressure, C_p. The magnitude of C_p is always greater than C_v; however, this difference is very slight for most solid materials at room temperature and below. Table 1 lists C_p values for various metallic elements.

Thermal Conductivity. Thermal conduction is the phenomenon by which heat is transported/transferred from high- to low-temperature regions of a substance. The property that characterizes the ability of a material to transfer heat is the *thermal conductivity,* which is defined as:

$$q = -k(dT/dx)$$

where q denotes the heat flux, or heat flow, per unit time per unit area (area being taken as that perpendicular to the flow direction), k is the thermal conductivity, and dT/dx is the temperature gradient through the conducting medium. The units for q and k are W/m^2 and W/m × K, respectively. (Room-temperature k values for various metals are given in Table 1.) It should be noted that the above equation is valid for only steady-state heat flow, that is, for situations in which the heat flux does not change with time. The minus sign in the equation indicates that the direction of heat flow is from hot to cold, or down the temperature gradient.

Because the thermal vibration of the free electrons in metallic crystals is a major contributor to the high thermal conductivity of solid metals (along with ionic vibration), the values of the thermal and electrical conductivities of a metal at any given temperature are related. The ratio between the two is called the Wiedemann-Franz ratio (k/σ), which was developed by Gustav Heinrich Wiedemann and Rudolf Franz and is about 1.6×10^{-6} at 20 °C. Further, because electrical resistivity is nearly proportional to the absolute temperature, the value $k/\sigma T$, called the Lorentz number (after Henrick Anton Lorentz), is approximately constant. A more exact relation between the two conductivities, however, is defined by the Bungardt and Kallenbach equation:

$$k = \mathrm{A} \times \sigma T + B \times T$$

where A and B are the constants for the free-electron and ionic contributions, respectively, for a given metal. Because of the difficulty involved in measuring thermal conductivity compared to electrical resistivity, this relation is useful in estimating the thermal conductivities of alloys as well as metals.

It should be noted that because both electrical and thermal conductivities rely on the migration of free electrons, temperature is not the only factor that affects these properties. Anything that distorts the crystal structure, such as thermal vibrations of the ions, crystal vacancies and dislocations, grain boundaries, interstitial and solute ions, and elastic and plastic strain, will increase resistance to conduction.

Thermal diffusivity is a useful measure of the speed at which heat spreads throughout a metal object, and this property can be calculated by dividing the thermal conductivity by the product of the specific heat capacity and the density of the metal. The units of thermal diffusivity are m^2/s, and the value describes the rate at which the spherical area within the object that is at a given temperature expands from a point heating source.

Electrical Properties

One of the most important electrical characteristics of a solid material is the ease with which it transits an electric current. *Ohm's law* (after Georg Simon Ohm) relates the current, I, to the applied voltage, V, as follows:

$$V = IR$$

where R is the resistance of the material through which the current is passing. The units for V, I, and R are volts (V), amperes (A), and ohms (Ω = V/A). The value of R is influenced by specimen configuration, and for many materials is independent of current. The *resistivity*, designated ρ, is independent of specimen shape, but related to R through the expression:

$$\rho = RA/l$$

where l is the distance between the two points at which the voltage is measured, and A is the cross-sectional area perpendicular to the direction of the current. The units for ρ are $\Omega \times$ m (often given as $\mu m\Omega \times$ m or $n\Omega \times$ m). From the expression for Ohm's law and the previous equation:

$$\rho = VA/Il$$

Sometimes, *electrical conductivity*, σ, is used to specify the electrical character of a material. It is simply the reciprocal of the resistivity, or $\sigma = 1/\rho$.

As shown in Table 1, metals exhibit a wide range of resistivities--from the low resistivity (high conductivity) of silver and copper to the high resistivity (low conductivity) of manganese and bismuth. Resistivity values of metals increase with increasing temperature.

Also as shown in Table 1, the semimetals boron, carbon, silicon, white phosphorus, sulfur, germanium, and tellurium have electrical resistivities that are intermediate between those of metal conductors and nonmetal insulators. Therefore, they are called *semiconductors*. Their resistivities range from about 10^3 to 10^{13} $\Omega\cdot$ m, and they decrease with increasing temperature over some temperature range.

Magnetic Properties

All metals have magnetic properties, and these properties are important in many industrial applications. The *magnetic moments* are generated by the movements of the electrically charged electrons that orbit the atomic nuclei making up the crystal structure of the metal. Each electron generates magnetic moments from two sources, as shown in Fig. 1; one source is its orbiting and the other is its spinning as it orbits. Because these moments have specific directions, the orbital moments of some electron pairs in each individual atom can cancel each other. This also applies to spin moments. The resulting magnetic moment for each atom, then, is the net sum (rather than the total) of the individual moments of its electrons. Therefore, for atoms having completely filled electron shells, there is complete cancellation of electron moments, and the material is not capable of being permanently magnetized.

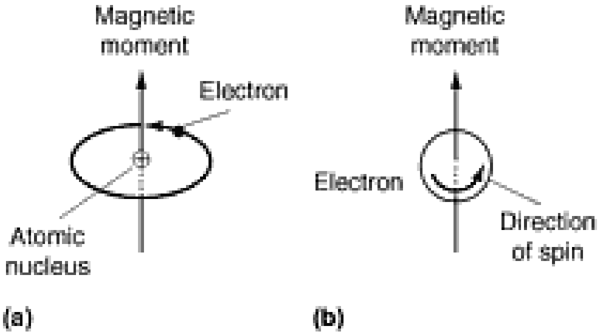

Fig. 1 Sources of magnetic moments. (a) Orbiting electron. (b) Spinning electron

One measure of the magnetism of a material is its *magnetic permeability*. Magnetic permeability is a measure of the tendency of magnetic lines of force to pass through a metal in comparison to empty space. Another measure of the magnetism of a material is its *magnetic susceptibility*. Magnetic susceptibility is the ratio of the intensity of magnetization in a metal to the magnetizing force to which the metal is subjected. Relative permeability and susceptibility are both unitless, but the values of susceptibility in SI units (referred to as meter-kilogram-second or mks units) are 4 πgreater than the values in cgs-emu (centimeter-gram-second electromagnetic unit) units. (The values of relative permeability are identical in SI and cgs-emu units.)

The magnetic susceptibility, μ, of a material is defined by the equation:

$$B = \mu H$$

where H is the strength of a magnetic field applied to a material and B is the density of magnetic flux induced in the material. As the applied field is increased, the magnetic flux density also increases until a saturation level for the material is reached (see Fig. 2).

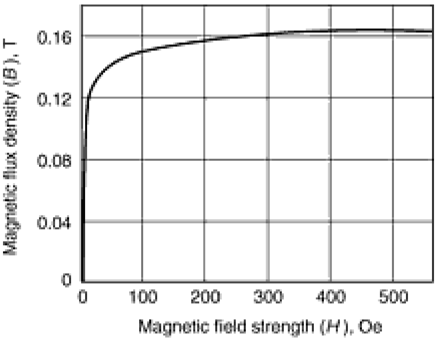

Fig. 2 Magnetization curve for polycrystalline iron

Another property of magnetic materials is its *saturation magnetic moment* (see Table 3). The value of the saturation magnetic moment of a material is the ratio of the magnetic moment per atom of the material at magnetic saturation to the spin magnetic moment per electron in the material.

Table 3 Magnetic phase transition temperatures of metallic elements

Chemical symbol	Atomic number	Allotrope	Phase transition temperature (T_c), K	Type of magnetic ordering(a)	Phase transition temperature (T_{c2}), K	Type of magnetic ordering(a)	Phase transition temperature (T_{c3}), K	Type of magnetic ordering(a)	Saturation magnetic moment, μ_B
Ce(b)	58	β-dcph	13.7	AC?	12.5	AC?	. . .	. . .	2.61
		γ-fcc	14.4	AC?	. . .	. . .	. . .	. . .	. . .
Cm	96	α-dcph	52	AC	. . .	. . .	. . .	. . .	. . .
Co	27	fcc	1388 (1115 °C)	FM	. . .	. . .	. . .	. . .	1.715
Cr	24	bcc	312.7 (39.5 °C)	AI	. . .	. . .	. . .	. . .	0.45
Dy	66	α-cph	179.0	AI	89.0	FM	. . .	. . .	10.33
Er	68	cph	85.0	AI	53	AC	20.0	CF	9.1
Eu	63	bcc	90.4	AC	. . .	. . .	. . .	. . .	5.9
Fe(c)	26	α-bcc	1044 (771 °C)	FM	. . .	. . .	. . .	. . .	2.216
		γ-fcc	67	AC	. . .	. . .	. . .	. . .	0.75
Gd	64	α-cph	293.4 (20.2 °C)	FM	. . .	. . .	. . .	. . .	0.75
Ho	67	cph	132.0	AI	20.0	CF	. . .	. . .	10.34
Mn	25	α-bcc	100	AC	. . .	. . .	. . .	. . .	(d)
Nd	60	α-dcph	19.9	AI	7.5	AC	. . .	. . .	1.84
Ni	28	fcc	627.4 (354.2 °C)	FM	. . .	. . .	. . .	. . .	0.616
Pm	61	α-dcph	98	FM?	. . .	. . .	. . .	. . .	0.24

Pr	59	α-dcph	0.06	AC	. . .	. . .	. . .	. . .	0.36
Sm	62	α-rhomb	106	h, A(e)	13.8	c, A(e)	. . .	. . .	0.1
Tb	65	α-cph	230.0	AI	219.5	FM	. . .	. . .	9.34
Tm	69	cph	58.0	AI	40-32	FI	. . .	. . .	7.14

Source: J.J. Rhyne, *Bull. Alloy Phase Diagrams*, Vol 3 (No. 3), 1982, p 402

(a) FM, transition from paramagnetic to ferromagnetic state; AC, transition to periodic (antiferromagnetic) state that is commensurate with the lattice periodicity (e.g., spins on three atom layers directed up followed by three layers down, etc.); AI, transition to periodic (antiferromagnetic) state that is generally not commensurate with lattice periodicity (e.g., helical spin ordering); CF, transition to conical ferromagnetic state (combination of planar helical antiferromagnetic plus ferromagnetic component); and FI, transition to ferromagnetic periodic structure (unequal number of up and down spin layers).

(b) Ce exists in five crystal structures, two of which are magnetic (γ-fcc; and β-dcph). γCe is estimated to be antiferromagnetic below 14.4 K by extrapolation from fcc Ce-La alloys. (αCe does not exist in pure form below ≈ 100 K.) βCe is thought to exhibit antiferromagnetism on the hexagonal lattice sites below 13.7 K and on the cubic sites below 12.5 K.

(c) Magnetic measurements quoted in table for γFe are for fcc Fe precipitated in copper.

(d) The magnetic moment assignments of Mn are complex.

(e) h, A; c, A; indicate that sites of hexagonal and cubic point symmetry order antiferromagnetically, but at different temperatures.

The magnetic properties of some metallic elements are listed in Tables 3 and 4. It should be noted that there are several types of magnetism found in metals, and the temperatures at which they change from one type to another are also given in Table 3. As seen in the table, iron is not the only metal to exhibit ferromagnetism. Cobalt, nickel, and possibly promethium also exhibit ferromagnetism at room temperature. Gadolinium and a few other rare earth metals are ferromagnetic at very low temperatures. *Ferromagnetic materials* are those in which, at temperatures below a characteristic temperature called the *Curie point* (after Pierre Curie), the magnetic moments of atoms or ions tend to be aligned parallel to one another without the presence of an applied field, thereby producing a "permanent" magnetic moment. Above the Curie point, these materials become paramagnetic. *Paramagnetic materials* are those within which the permanent-magnetic dipole moments of atoms or ions are only partially aligned and the magnetic induction (magnetic flux density) is only slightly greater than the applied magnetic-field strength. The permeability of a ferromagnetic metal can reach values of the order of 10^6 times that of empty space, while the permeability of a paramagnetic metal is only slightly greater than that of empty space.

Table 4 Room-temperature magnetic susceptibilities for paramagnetic and diamagnetic materials

Paramagnetics		**Diamagnetics**	
Material	**Susceptibility X_m (volume) (SI units)**	**Material**	**Susceptibility X_m (volume) (SI units)**
Aluminum	2.07×10^{-5}	Copper	-0.96×10^{-5}
Chromium	3.13×10^{-4}	Gold	-3.44×10^{-5}
Molybdenum	1.19×10^{-4}	Mercury	-2.85×10^{-5}
Sodium	8.48×10^{-6}	Silicon	-0.41×10^{-5}
Titanium	1.81×10^{-4}	Silver	-2.38×10^{-5}
Zirconium	1.09×10^{-4}	Zinc	-1.56×10^{-5}

There are three other types of magnetic materials. *Ferrimagnetic materials* are those in which the magnetic moments of atoms or ions tend to assume an ordered but nonparallel arrangement in a zero applied field below a characteristic temperature called the Néel point (after Louis E.F. Néel). *Antiferromagnetic materials* are those in which the magnetic moments of atoms or ions tend to assume an ordered arrangement in a zero applied field, such that the vector sum of the moments is zero below the Néel point. The permeability of antiferromagnetic materials is comparable to that of paramagnetic materials. Above the Néel point, both these materials become paramagnetic. *Diamagnetic materials* are those within which the magnetic induction is slightly less than the applied magnetic field. For diamagnetic materials, the permeability is slightly less than that of empty space, and the magnetic susceptibility is negative and small.

The response of ferromagnetic, paramagnetic, and diamagnetic materials is compared in Fig. 3. Additional information on the magnetic characteristics of metals and alloys can be found in the Section "Special-Purpose Materials" in this Handbook.

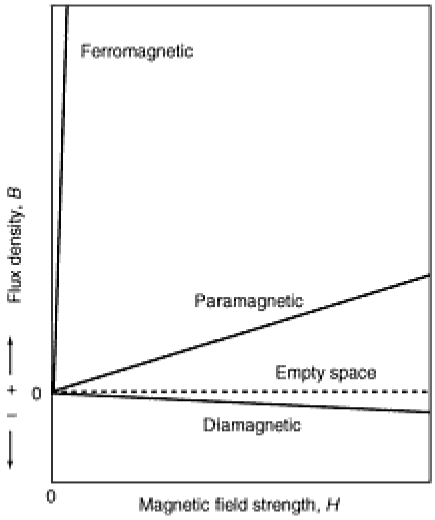

Fig. 3 Schematic of the flux density, *B*, versus magnetic field strength, *H*, for diamagnetic, paramagnetic, and

ferromagnetic materials

Optical Properties

Several optical properties of smooth, bare, unoxidized metal surfaces are important in some applications. Four of these are *solar reflectivity* (shininess in sunlight), *solar absorptivity* (warming by sunlight), *thermal emissivity* (radiation cooling from a warm body), and color. (The word ending "ance" is substituted for "ivity" when the properties are measured on a rough surface.) The reflectivities of metals are high, but their emissivities are low. It should be remembered, however, that the values of these properties apply only to smooth, clean, unoxidized bare surfaces, which are seldom found on metals and alloys in practical applications. Instead, the surfaces of metals are almost always covered with some kind of an oxide layer or paint, both of which have the relatively low reflectance, but high *emittance* of nonmetallics. Exceptions are the noble metals (see below), which are normally bare.

The surface of clean, bare, unoxidized metals is lustrous. The color in all but two instances ranges from silvery gray to various shades of white. The exceptions are the reddish color of copper and the red-yellow of gold, which is the result of their electron configurations. Because of their chemical activities, thin oxides rapidly form on freshly bare surfaces of most metals, and these oxides can affect their appearance (see below).

Radiation Properties

The properties that describe the transparency or opaqueness of metals to radiation are important in some industries. The transparency to x-rays of light metals is required for the holders of x-ray films, while absorption of x-rays by lead makes possible its use as a shielding material. The thermal-neutron cross section of a metal defines the extent to which that metal absorbs thermal (slow) neutrons from a nuclear reactor, and the low thermal-neutron cross section of zirconium makes it a good canning material for nuclear fuel.

Chemical Properties of Metals

The chemical property most important to structural use of a metal is its corrosion behavior. Most metals are basic in chemical behavior (will react with acids). But as stated above, because of the chemical activities of the metallic elements, thin oxides rapidly form on freshly bare surfaces of most metals. Ruthenium, rhodium, palladium, silver, osmium, iridium, platinum, and gold are the exceptions. These eight metals have such low chemical activity that they are called *noble metals.*

The physical and chemical properties of the oxides that form on the nonnoble metals, however, differ from metal to metal. Physically, some oxides cohere tightly to their base metal, while others readily spall or flake off and expose fresh base metal to the air. Also, some oxides are very dense and impervious to diffusion and allow very little oxygen to penetrate to the base metal, while others are quite porous and allow oxidation of the base metal to readily continue.

The oxides also differ in their chemical behavior, and this affects their compatibility with various environments (including paints). Many of these oxides are also basic in chemical behavior. The oxides of the alkali metals are strong bases, while those of the alkaline earth metals are moderately strong bases. The oxides of the metals in group 13 of the periodic table, such as aluminum, are amphoteric (react with both strong acids and bases). The oxides of most transition elements are weak bases, but many of these are amphoteric. This includes ferric oxide (Fe_2O_3), which may react with strong bases. In general, the metals farther to the right of the periodic table form oxides that are increasingly weaker bases. While the metal oxides are protective in many situations, it also should be noted that most bare structural metals are very chemically active, and whenever their protective oxide film breaks down, the reaction to the environment can be quite rapid.

General Corrosion Behavior of Metals

The general corrosion behaviors of several metals used in construction are discussed below. More detailed information on corrosion characteristics can be found in the Sections of this Handbook that deal with these metals and their alloys.

Tin also is protected by a very thin layer of oxide (SnO_2) that is relatively impervious, adherent, and quite transparent. This oxide layer has the good thermal emittance of nonmetallics, but because it is very thin and quite transparent, the surface has almost the same good reflectivity of bare tin.

Copper. The corrosion product predominantly responsible for the protection of copper in aqueous environments is Cu_2O. This oxide layer is not impervious, but is adherent and provides excellent protection against further corrosion. In marine environments, an attractive and protective green patina forms, which consists of a film of copper chloride or carbonate, sometimes with a inner layer of Cu_2O.

Aluminum. The oxide that first forms on aluminum is also both quite impervious to diffusion and quite coherent (although some of the gray oxide will rub off). Therefore, oxidation of the base metal slows almost to a stop while the oxide film is still so thin that it is quite transparent (about 1 nm thick). The corrosion product that forms on the surface of bare metals exposed to air, however, is seldom a simple oxide such as the thin barrier layer of Al_2O_3 that forms aluminum. In moist air, a more permeable layer of hydrated oxide, $Al_2O_3{\cdot}3H_2O$, forms over the oxide layer on aluminum, and it is the chemical properties of these two corrosion products that controls the chemical behavior of aluminum.

Titanium. The oxide that typically forms on titanium in aqueous environments is TiO_2, but can consist of mixtures of other oxides, such as Ti_2O_3 and TiO. The TiO_2 film is typically less than 10 nm thick and, therefore, also invisible. Like tin, copper, and aluminum, the oxide surface has both good emittance and good reflectivity. In addition, it is impervious to oxygen (and hydrogen) and is highly chemical resistant and attacked by very few substances.

Iron. In contrast to the metals described above, the oxide that forms on iron is much less dense. Therefore, the layer of iron-oxide rust is rather permeable and builds up fairly rapidly to a thickness that is easily seen (and its reddish color enhances its visibility), and the layer will continue to thicken until all the base metal is converted. The rust also readily flakes and rubs off. This rust, however, consists of hydrated oxides rather than simple oxides, but these hydrated oxides can lose water due to drying and revert to the anhydrous FeO and Fe_2O_3. In addition, a layer of Fe_3O_4 ($FeO{\cdot}Fe_2)_3$) often forms between the FeO and Fe_2O_3, and various crystal forms of FeOOH have also been found to exist in the complicated system of compounds that form on iron (and steel). The composition of this rust film and its corrosion behavior depends on oxygen availability, humidity, temperature, and the levels of atmospheric pollutants present. In aqueous environments, pH affects corrosion of iron and steel. While the rust film offers some protection to iron and steel in alkaline environments, the evolution of hydrogen at low pH tends to diminish this protection.

Magnesium. The film that first forms on magnesium is the hydroxide, $Mg(OH)_2$. This hydroxide then reacts with any carbonic acid in the environment to form various hydrated carbonates, including $MgCO_3{\cdot}H_2O$, $MgCO_3{\cdot}5H_2O$, and $3MgCO_3{\cdot}Mg(OH)_2{\cdot}3H_2O$. In atmospheres contaminated with sulfur compounds, magnesium sulfites or sulfates such as $MgSO_4{\cdot}7H_2O$ may also be present in the film. This gray film is permeable, but also is fairly adhesive and does not readily rub off.

Zinc is highly resistant to atmospheric corrosion due to the formation of insoluble basic carbonate films that protect the metal surface.

Mechanical Properties

Elasticity. When a crystal is stressed by an internal or external load, the lattice responds by relative movement of the atoms (ions) in it in a manner that tends to relieve that stress. The measure of the change in size of the crystal or multicrystalline object caused by the stress is strain. When the load is removed, the crystal or object will return to its original size provided that all the atoms in the crystal or object keep their original neighbors. When this provision is met, the strain is elastic (the crystal or object has sustained *elastic deformation*) and amount of strain is directly proportional to the amount of stress placed on the crystal or object. This proportionality is called *Hooke's law* (after Robert Hooke).

The relation between *applied stress* and *elastic strain* is called the *modulus of elasticity* of the material. The modulus obtained under unidimensional tension or compression loading is called *Young's modulus, E* (after Thomas Young), while torsion or shear loading gives the *modulus of rigidity* or *shear modulus, G.* Young's modulus and the shear modulus are related by the formula below, which involves the *Poisson's ratio,* ν (after Siméon Denis Poisson), which is the ratio of lateral strain to axial strain in a stressed material:

$$\nu = (E - 2G)/2G$$

Hydrostatic compression causes materials to contract in volume. The ratio of the unit change in volume to the mean normal (perpendicular) compressive stress is called the *compressibility,* β, of the material. The inverse of compressibility (the ratio of the mean normal pressure on the material to its unit contraction) is called the *bulk modulus, K*, of the material. The values of elastic moduli of several metals are listed in Table 5.

Table 5 Mechanical properties of selected metals at room temperature

Metal	**Young's modulus (*E*), GPa**	**Shear modulus (*G*), GPa**	**Poisson's ratio, ν**	**Yield strength, MPa**	**Tensile strength, MPa**	**Elongation, %**
Aluminum	67	25	0.345	15-20	40-50	50-70
Beryllium	303	142	0.07	262-269	380-413	2-5
Cadmium	55	19.2	0.43	. . .	69-83	50
Chromium	248	104	0.210	. . .	83	0
Cobalt	211	80	0.32	758	945	22
Copper	128	46.8	0.308	33.3	209	33.3
Gold	78	27	0.4498	. . .	103	30
Iron	208.2	80.65	0.291	130	265	43-48
Lead	26.1	5.6	0.44	9	15	48
Magnesium	44	16.3	0.35	21	90	2-6
Molybdenum	325	260	0.293	200	600	60
Nickel	207	70	0.31	59	317	30
Niobium	103	37.5	0.38	. . .	585	5
Silver	71.0	26	0.37	. . .	125	48
Tin	44.3	16.6	0.33	9	. . .	53
Titanium	120	45.6	0.361	140	235	54
Tungsten	345	134	0.283	350	150	40
Zinc	69-138	. . .	. . .	. . .	. . .	. . .

Zirconium	49.3	18.3	0.35	230	. . .	32

Plasticity. When the *elastic limit* of the bulk material is exceeded and not all of the atoms in a crystal or object under stress keep their original neighbors (due to slip and/or twinning), a *plastic strain* increment is added to the elastic strain to make up the *total strain* on the crystal or object. At this point, the material is said to have begun yielding. Then when the load is removed, the plastic strain remains and the crystal or object has sustained *permanent deformation,* producing a *permanent set.*

Stress-Strain Curves. Plots of the relation between applied *nominal stress* (load divided by original cross section) and resulting strain (unit deformation) that are determined for a material specimen reveal much information about the mechanical properties of that material. Figure 4 shows a tensile stress-strain curve typical of a pure metal. A specimen having a reduced-cross-section "gage" section is prepared, the area of that section is measured, and a standard gage length (often 50 mm, or 2 in.) is marked on the section. Upon initial loading, the metal specimen elongates and laterally contracts (or laterally expands if the load is in compression), and the curve of strain versus stress follows the modulus line until it reaches the *proportional limit,* which is essentially the same point as the elastic limit. This limit is so low in most metals that it is difficult to determine an accurate value for the modulus of elasticity of the metal from a stress-strain curve. Therefore, this value for metals is often determined instead by a sonic vibrational test.

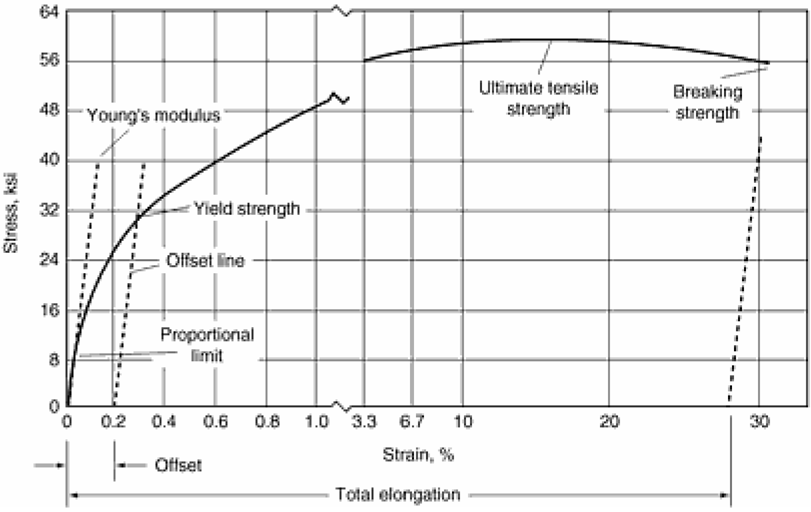

Fig. 4 Typical tension stress-strain curve for a nonferrous metal

Brittle metals, such as chromium, will fracture upon loading to the elastic limit rather than sustain plastic deformation. Upon loading of ductile metals beyond the elastic limit, the addition of plastic deformation to the elastic strain causes the total strain to increase at a faster rate than before and the plot curves off from the modulus line. Because it also is difficult to determine on a stress-strain curve where yielding begins, an arbitrary definition of "yielding" is used. In many testing standards, the *yield strength* of most metals is defined as the stress at which a line parallel to the modulus line, but offset from it by 0.2% strain, intersects the curve (see Fig. 4).

It should be remembered that the stress applied to the specimen is normally the nominal stress rather than *true stress.* In the initial portion of the plot, the amount of lateral contraction (thinning) of the specimen is distributed along the entire test length of the specimen and is therefore so small that the nominal and true stress are almost identical. But in the latter portion of the test, *necking* of a tensile specimen occurs. That is, thinning begins to concentrate near the region where fracture will eventually occur. This necking can often become so pronounced that the nominal stress will decrease upon additional loading, as shown in Fig. 4, even though the true stress continues to increase until fracture occurs.

A plot of nominal tension stress versus strain such as shown in Fig. 4 is sometimes called an *engineering stress-strain curve* to distinguish it from a *true stress-strain curve* (see also Fig. 5). The high point on an engineering stress-strain curve is defined in test standards as the *ultimate tensile strength* of the specimen, or simply the *tensile strength.* The point of fracture is called the *fracture strength* or *breaking strength.* Upon fracture, the elastic energy in the specimen is released and the elastic strain is recovered. The plastic strain remaining in specimen, called the *total elongation,* is then determined by fitting the broken pieces together and measuring the new distance between the gage marks. The *reduction in area* of the broken specimen is determined by measuring the dimensions of the necked-down region at the fracture and comparing that cross-sectional area to the original cross section. Besides tensile and compressive stress-strain curves, occasionally torsion and/or bearing curves are determined. Table 5 lists typical strengths and total elongations of several annealed metals.

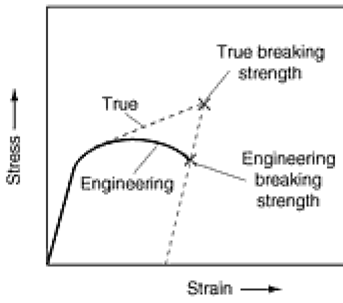

Fig. 5 True stress-strain curve versus engineering stress-strain curve

Modern design concepts sometimes require better descriptions of stress-strain behavior than afforded by tabular values of modulus, strength, and elongation. Therefore, stress-strain curves themselves are sometimes reproduced, but usually only the portion covering the first few percent of elongation. Other times, strain is not shown on the final plot. Instead, the slope of the stress-strain curve is described by plotting the secant modulus or the tangent modulus. As shown in Fig. 6, the *tangent modulus* is defined as the slope of a stress-strain curve at a specified point on that curve; the *secant modulus* is the slope of a line connecting the origin of a stress-strain curve with a specified point on that curve.

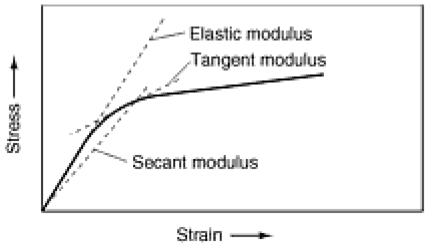

Fig. 6 Three types of modulus ratios that can be derived from a stress-strain curve

The stress-strain curves of iron containing even a small amount of carbon are different from those of pure metals. As seen in Fig. 7, the point at which yielding begins, called the *yield point* or *upper yield point,* is quite sharply defined. This is because as soon as the stress corresponding to this point is exceeded, the stress required for plastic deformation noticeably drops to a level called the *lower yield point.* The plot then begins to rise in a curve similar to that for pure metals. The stress at the upper yield point, rather than the lower yield point, is usually reported as the yield strength of these materials.

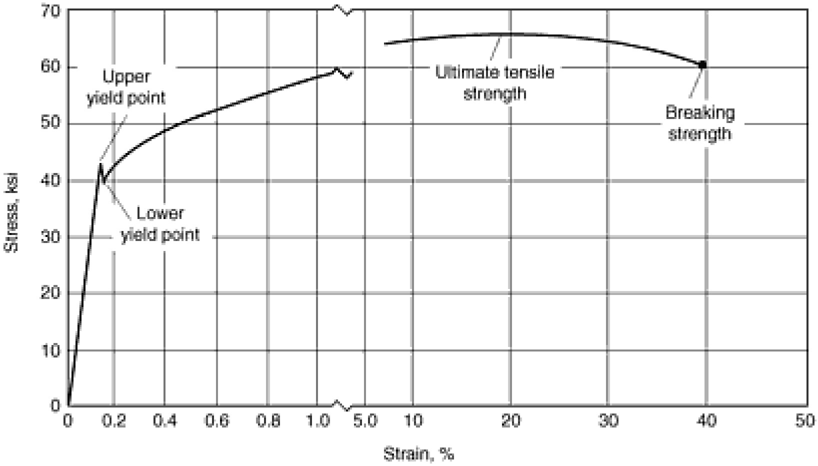

Fig. 7 Typical tension stress-strain curve for iron containing 0.15% C

Creep is the term used to describe the time-dependent plastic deformation, *creep strain,* that occurs when a material is subjected to constant nominal stress. When the non-time-dependent strain that results from the initial loading is added to the creep strain, the result is called *total strain.* (The thermal expansion that occurs upon heating to the test temperature, however, is not included.) Most creep testing is done under tension and at temperatures that are relatively high for the material being tested, and the terms *creep extension* and *total extension* are used. As shown in Fig. 8, the rate of creep strain upon initial loading is fairly rapid, but decreases with time; this is called *primary creep.* The creep rate then reaches a minimum and a fairly constant rate for a period of time, which is called *secondary creep.* In *third-stage creep* or *tertiary creep,* the creep rate begins to increase again and continues to increase until the specimen breaks (if the test is continued to this point). The relative portions of the total time to rupture taken by these three stages depends on several factors, and in some tests, the secondary stage becomes a point on the graph where it changes from decreasing to increasing curvature.

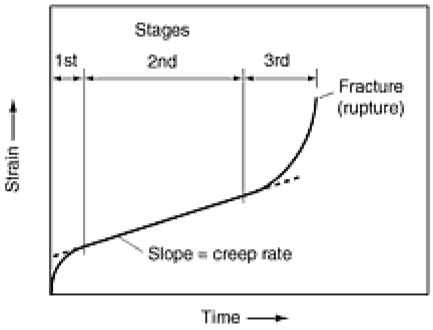

Fig. 8 The three stages of a creep curve

The results of creep tests are reported in a variety of ways. Sometimes, the results for a given temperature (especially short-time, high-temperature tests) are reported in the form of *isochronous stress-strain curves,* which are curves constructed from equal-time points on the stress-strain relationships determined in the creep test (see Fig. 9). The elastic portion of such isochronous stress-strain curves is added by using the modulus value for the test temperature determined independently. The stress that causes a specified strain at that temperature is then called the *creep strength* of the material for those conditions. (The term creep strength is sometimes also used to describe the stress that will cause a specified rate of secondary creep at that temperature.) Other times, equal-strain results for a given temperature are plotted on stress-time graphs.

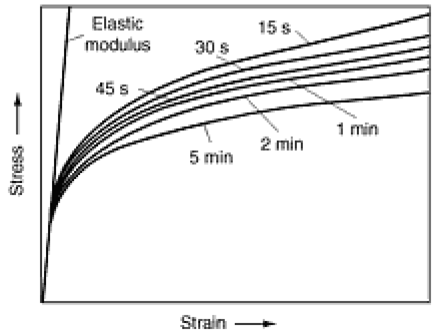

Fig. 9 Isochronous stress-strain curves for specimens of a material creep tested at a given temperature

When a creep test is continued until the specimen ruptures, the test is often called a *creep-rupture* or *stress-rupture* test, and the results are reported on a plot of stress versus time to rupture.

Fatigue. The tendency of a material to break under conditions of repeated cyclic stresses is called *fatigue.* Fatigue fractures are different from the ductile fractures that usually result from regular tension and creep loading of most metals. Instead, fatigue fracture is caused by the propagation of cracks that initiate at a single point or at a few points in the material, and fatigue fractures are always brittle fractures. Most parts and fatigue specimens contain points of *stress concentration,* such as surface roughness or changes in part or specimen section, at which stress is concentrated and where fatigue cracking initiates. The amount of concentration can be determined (based on purely elastic behavior) and is reported as the *theoretical stress-concentration factor* or simply the *stress-concentration factor,* K_t. The *fatigue-strength reduction factor* or *fatigue-notch factor* can be determined by dividing the fatigue strength of smooth (unnotched) specimens by the fatigue strength of notched specimens. Comparing the fatigue-strength reduction factor to the theoretical stress-concentration factor gives a measure of the sensitivity of the material to notches when under cyclic loading; *notch sensitivity* is the fatigue factor divided by K_t - 1 and often is expressed as a percentage.

Several different fatigue tests have been developed, each designed to replicate the loading conditions found in specific industrial applications. The rotating-beam test replicates the loading of a railroad axial; the plate-bending test, a leaf spring; the axial test, connecting rods and chain links. Some tests run under constant load, while others run under constant strain. Therefore, tabular values of fatigue strength or fatigue limit are of value mainly in material selection, rather than useful in actual design calculations.

The stress in a fatigue test usually is cycled between a maximum tensile stress and a minimum tensile stress or between a maximum tensile stress and a maximum compression stress. The ratio of these extremes (where compression is considered a negative stress) is called the *stress ratio, R.* The ratio for fully reversed stress then becomes -1. Other terms used to describe a fatigue stress include mean *stress* (the stress midway between the extremes), the *stress range* (the stress variation between the extremes), and the *stress amplitude* (the stress variation between the mean stress and one of the maximums).

The results of fatigue test are usually reported in the form of plots of stress versus number of cycles to fracture, called *S-N* curves. In these plots, the number of cycles is usually plotted on a logarithmic scale (and sometimes stress is also). Most metals have *S-N* curves that continually show longer lives at lower stresses, and the *fatigue strength* of the material must be reported for a given number of cycles (as well as the stress ratio for the test and the stress-concentration factor if the specimen contains a notch). For steels, however, the curve breaks off and becomes essentially horizontal at some stress level called the *fatigue limit* (see Fig. 10).

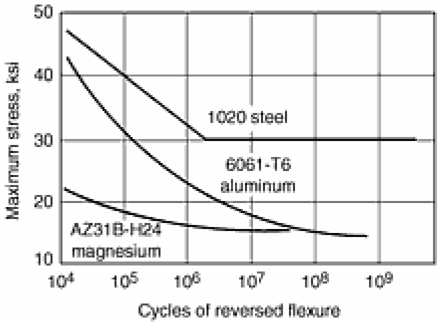

Fig. 10 Comparative fatigue curves

Some fatigue tests are conducted using a fracture-mechanics approach. This is described in the Section "Failure Analysis" in this Handbook.

Toughness. Generally speaking, *toughness* is a measure of the amount of energy a material absorbs during straining to fracture. Specimen shape as well as the manner of load application are important in toughness determination. For dynamic (high-strain-rate) loading conditions and when a notch (or point of stress concentration) is present, notch toughness is assessed by using an impact test (see the Section on "Mechanical Testing" in this Handbook). A special measure of toughness is used in *linear fracture mechanics* called *fracture toughness* (the ability of a material to resist fracture when a crack is present). This is a scaling factor, also called the *critical stress-intensity factor, K,* that describes the intensification of applied stress at the tip of a crack of known size and shape at the onset of rapid crack propagation. Details on fracture toughness and fracture mechanics can be found in the Sections "Mechanical Testing" and "Failure Analysis" in this Handbook.

For the static (low-strain-rate) situation, toughness can be determined from the results of a tensile stress-strain test. It is the area under the stress-strain curve up to the point of fracture.

Hardness is the resistance of a material to plastic indentation. While the measurement of hardness can involve only a simple scratch test or bounce test, it usually involves the amount of indentation caused by the application of a hard indenter of some standard shape and material. Hardness values are roughly proportional to the strength of a metal (see, for example, the hardness conversion tables for steels in the Section "Glossary of Terms and Engineering Data") and can give an indication of its wear properties (abrasion resistance). Therefore, hardness values can be useful during selection of a suitable material for an application. They also are very useful during quality-control operations, but the values cannot be applied directly during the design of a part. Hardness tests are described in the Section "Mechanical Testing" in this Handbook.

Introduction and Overview of Design Considerations and Materials Selection

Introduction

ENGINEERING DESIGN can be defined as the creation of a product that satisfies a certain need. A good design should result in a product that performs its function efficiently and economically within the prevailing legal, social, safety, and reliability requirements. To satisfy such requirements, the design engineer has to take into consideration many diverse factors:

- *Function and consumer requirements,* such as capacity, size, weight, safety, design codes, expected service life, reliability, maintenance, ease of operation, ease of repair, frequency of failure, initial cost, operating cost, styling, human factors, noise level, pollution, intended service environment, and possibility of use after retirement
- *Material-related factors,* such as strength, ductility, toughness, stiffness, density, corrosion resistance, wear

resistance, friction coefficient, melting point, thermal and electrical conductivity, processibility, possibility of recycling, cost, available stock size, and delivery time

- *Manufacturing-related factors,* such as available fabrication processes, accuracy, surface finish, shape, size, required quantity, delivery time, cost, and required quality

Figure 1 illustrates the relationship among the previously mentioned groups. The figure also shows that there are other secondary relationships between material properties and manufacturing processes, between function and manufacturing processes, and between function and material properties.

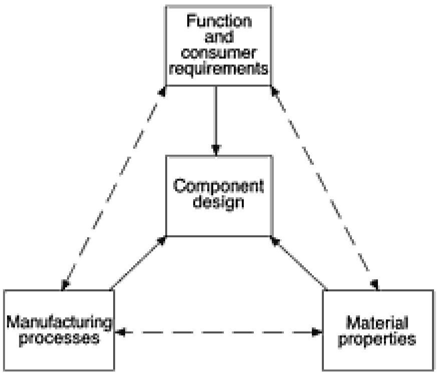

Fig. 1 Factors to consider in component design. Source: Ref 1

Figure 2 shows that engineering design is actually part of a much larger process of bringing new products to market. The name that has been coined for the complete process is the product realization process (PRP). As indicated in Fig. 2, engineering design takes place approximately between marketing and manufacturing within the total PRP of a firm. Engineering design, however, is not an isolated activity. It influences, and is influenced by, all other parts of a manufacturing business. Unfortunately, the relationship between design and other sectors of a manufacturing business has not been sufficiently recognized in the past. Recently, however, mostly in response to the pressures of international competitiveness, new approaches to product design and development have arisen to improve quality, drive down cost, and reduce product cycle time. Generally called *concurrent engineering,* the product uses product development teams of experts from all functions--design, manufacturing, marketing, and so forth--to work together from the start of the product design project. This opens new opportunities for better materials selection and has resulted in the development of new computer-based design tools.

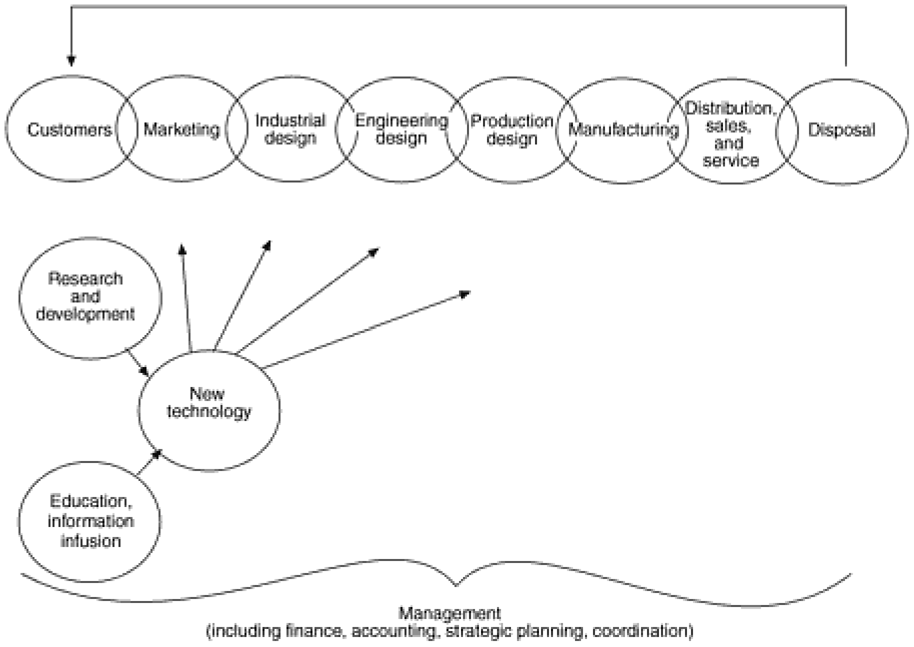

Fig. 2 Engineering design as a part of the product realization process

This introductory article, as well as the other articles that follow on "Design Factors" and "Factors in Materials Selection," discuss the various roles and responsibilities of materials engineers in a product realization organization and suggest new and different ways in which materials engineers can benefit their organizations. The integration of material, process, and product design relies on individuals who are trained in materials selection and can work in a team environment. Often it is the materials engineer/specialist, familiar with the conflicting needs of design, production, and marketing, who can assume the role of mediator to focus on the final product.

Reference

1. M.M. Farag, *Selection of Materials and Manufacturing Processes for Engineering Design,* Prentice Hall, London, 1989

Key Considerations for Design

The Design Process. The role of the materials engineer during the design process can take many paths. The task may simply be to design a "new" part that is nearly identical to an existing part and is expected to be used in similar ways. In this case, it may be possible to use the same material and processing used for the existing part. Alternatively, the task may be to design and select material for a new part. Obviously, this is a much more complex task and requires knowledge of loads, load distributions, environmental conditions, and a host of other performance factors (including customer expectations) and manufacturing-related factors.

In addition to a knowledge of the required performance characteristics, the materials selector is responsible for defining and accounting for manufacturing-induced changes in material properties. Different production methods, as well as controlled and uncontrolled thermal and mechanical treatments, will have varying effects on the performance properties and the cost of the final part or assembly. Often, it is by relating the varying effects of manufacturing processes to customer needs that one manufacturer develops an advantage over another product, using essentially the same material and process combinations.

It is critical to understand and accept that the choice of manufacturing processes is frequently not under the direct control of the materials selection expert. In fact, by the time the concept and initial configuration of a design is committed to paper, or to a computer-aided design (CAD) system, the manufacturing processes and sequence of processes required to produce a product cost effectively are normally fixed. They are no longer variables that can be controlled without redesign.

Criteria and Concepts in Design. Material selection involves more than meeting minimum property requirements for strength, fatigue, toughness, corrosion resistance, or wear resistance. There are numerous options for product design and materials selection, and frequently they cannot be quantified. This precludes the use of mathematical optimization routines and shifts the emphasis to experience. Experience is essential in dealing with these "soft issues" related to qualitative non-property considerations.

The design must be producible. This means robust processes must be selected that have known statistical variation and will yield features or complete parts that lie well within the specification limits. This design for manufacturability approach is becoming popular, is an integral part of an integrated product development team's tool box, and has been demonstrated to be effective in improving quality and reducing cost.

Designing to minimize the total costs to the consumer during the expected product life (the life cycle cost) is yet another challenge. These costs include raw material, production, use, maintenance (scheduled or otherwise), and disposal or recycling costs. Some of these cost elements are unknown. This is where the combination of the art and skill of engineering faces its most severe test.

Similar issues arise when the safety, product liability, and warranty cost exposure aspects of product design and material selection are concerned. In many cases, alternate designs or materials could be chosen with no measurable difference. However, there are also many cases where a particular design and/or material choice could prevent an undesirable product failure mode. An understanding of how a part, assembly, or entire structure can fail and the ramifications of that failure are essential in providing a safe and reliable design.

The growing environmental and regulatory demand to consider the entire life cycle of a product could require the manufacturer to recover and recycle the product and process waste materials. This places renewed emphasis on considering all options. Changing the materials or the manufacture of a component involves designing an environmentally friendly product. Changing from chromium plating appears to be environmentally friendly, but today's chrome plating units are being constructed to operate in a zero discharge mode, so there is no obvious gain from eliminating the chrome. The anodizing process can be just as clean. Paint, on the other hand, is suffering severe scrutiny over both emissions during the painting process as well as subsequent mishandling by the consumer. And, changing a part body from metal to plastic is not necessarily a good solution because the recycling infrastructure is not yet adequate on a global level to effectively reclaim the material.

Another design factor is the repairability of a product. Automobiles are not intended to have accidents, but they do. Design and material selection only for initial cost and performance factors has led to the widespread use of one-piece plastic parts that are not repairable in many cases. Any product that costs more to repair than the owner finds acceptable will eventually suffer in the marketplace.

Key Considerations for Materials Selection

The selection of the correct material for a design is a key step in the process because it is the crucial decision that links computer calculations and lines on an engineering drawing with a working design. Materials and the manufacturing processes that convert the material into a useful part underpin all of engineering design. The enormity of the decision task in materials selection is given by the fact that there are well over 100,000 engineering materials from which to choose. On a more practical level, the typical design engineer should have ready access to information on 50 to 80 materials, depending on the range of applications.

The importance of materials selection in design has increased in recent years. The adoption of concurrent engineering methods (see following discussion) has brought materials engineers into the design process at an earlier stage, and the importance given to manufacturing in present day product design has reinforced the fact that materials and manufacturing are closely linked in determining final properties. Moreover, world pressures of competitiveness have increased the general level of automation in manufacturing to the point where cost of materials comprise 50% or more of the cost for most products.

Relation of Materials Selection to Design. An incorrectly chosen material can lead not only to failure of the part but also to unnecessary cost. Selecting the best material for a part involves more than selecting a material that has the properties to provide the necessary performance in service; it is also intimately connected with the processing of the material into the finished part (Fig. 2). A poorly chosen material can add to manufacturing cost and unnecessarily increase the part cost. Also, the properties of the material can be changed by processing (beneficially or detrimentally), and that may affect the service performance of the part.

With the enormous combination of materials and processes to choose from, the task can be done only by introducing simplification and systemization. Design proceeds from concept design, to embodiment (configuration) design, to detail (parametric) design, and the material and process selection then becomes more detailed as the design progresses through this sequence.

At the concept level of design, essentially all materials and processes are considered rather broadly. The materials selection methodology and charts developed by Ashby (Ref 2) are highly appropriate at this stage. The decision is to determine whether each design concept will be made from metal, plastics, ceramic, composite, or wood, and to narrow it to a group of materials. The precision of property data needed is rather low. If an innovative material is chosen, it must be done at the conceptual design step because later in the design process too many decisions have been made to allow radical change.

At the embodiment or configuration level of design, the emphasis is on determining the shape and approximate size of a part using engineering methods of analysis. Now the designer will have decided on a class of materials and processes, for example a range of aluminum alloys, wrought and cast. The material properties must be known to a greater level of precision.

At the detail or parametric design level, the decision will have narrowed to a single material and only a few manufacturing processes. Here the emphasis will be on deciding on critical tolerances, optimizing for robust design, and selecting the best manufacturing process using quality engineering and cost modeling methodologies. Depending on the criticality of the part, materials properties may need to be known to a high level of precision. At the extreme, this requires the development of a detailed data base from an extensive materials testing program.

In a more detailed approach to engineering design, Dixon and Poli (Ref 3) suggest a four-level approach to materials selection:

- *Level I.* Based on critical properties, determine whether the part will be made from metal, plastic, ceramic, or composite.
- *Level II.* Determine whether metal parts will be produced by a deformation process (wrought) or a casting process; for plastics determine whether they will be thermoplastic or thermosetting setting polymers.
- *Level III.* Narrow options to a broad category of material. Metals can be subdivided into categories such as carbon steel, stainless steel, and copper alloys. Plastics can be subdivided into specific classes of thermoplastics and thermosets such as polycarbonates and polyesters.
- *Level IV.* Select a specific material according to a specific grade or specification.

Thus material and process selection is a progressive process of narrowing from a large universe of possibilities to a specific material and process selection. Levels I and II are often sufficient for conceptual design. Level III is needed for embodiment (configuration) design and sometimes for conceptual design Level IV usually can be postponed until the detail (parametric) design.

For all the stages of engineering design, the problem solving methodology employed is called *guided iteration* (Ref 3). The steps in the guided iteration process are formulation of the problem, generation of alternative solutions; evaluation of the alternatives; and if these steps are unacceptable, redesign guided by the results of the evaluations. This methodology is fundamental to design processes. It is repeated hundreds or thousands of times during product design. It is used again and again in recursive fashion for the conceptual stage to select materials and processes, to configure parts and to assign numerical values to dimensions and tolerances (i.e., parametric design). Figure 3 summarizes the guided iteration methodology.

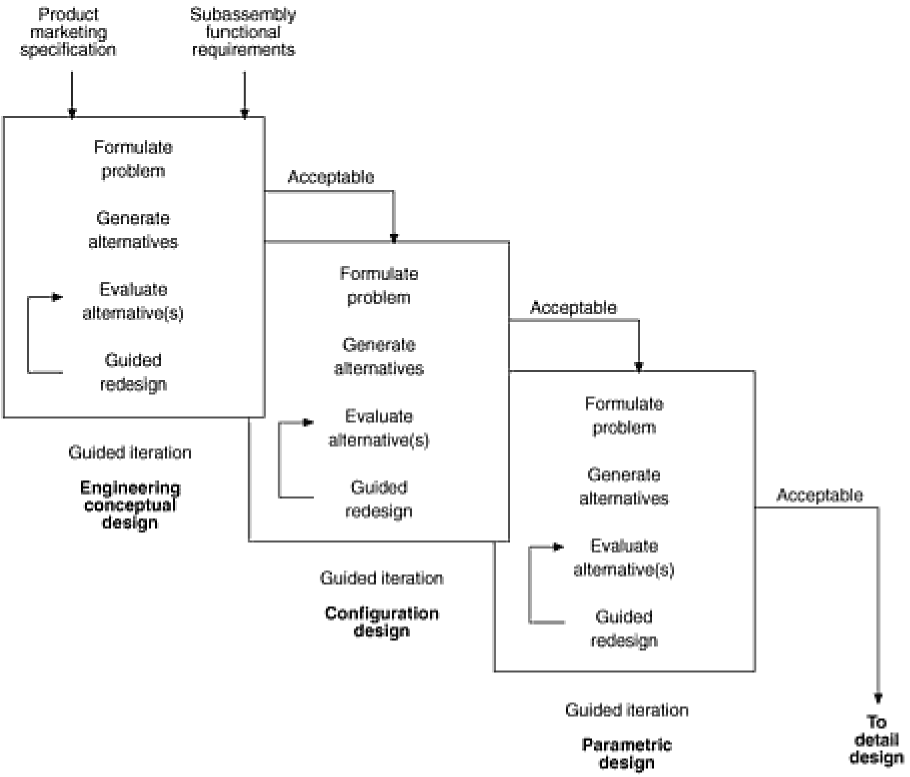
Product marketing specification
Subassembly functional requirements
Formulate problem
Generate alternatives
Evaluate alternative(s)
Guided redesign
Acceptable
Guided iteration
Engineering conceptual design
Formulate problem
Generate alternatives
Evaluate alternative(s)
Guided redesign
Acceptable
Guided iteration
Configuration design
Formulate problem
Generate alternatives
Evaluate alternative(s)
Guided redesign
Acceptable
Guided iteration
Parametric design
To detail design

Fig. 3 Guided iteration used for conceptual, configuration, and parametric design

Relation of Materials Selection to Manufacturing. The selection of a material must be closely coupled with the selection of a manufacturing process. This is not an easy task because there are many processes that can produce the same part.

The goal is to select the material and process that maximizes quality and minimizes the cost of the part. Figure 4 gives a breakdown of manufacturing processes into nine broad classes.

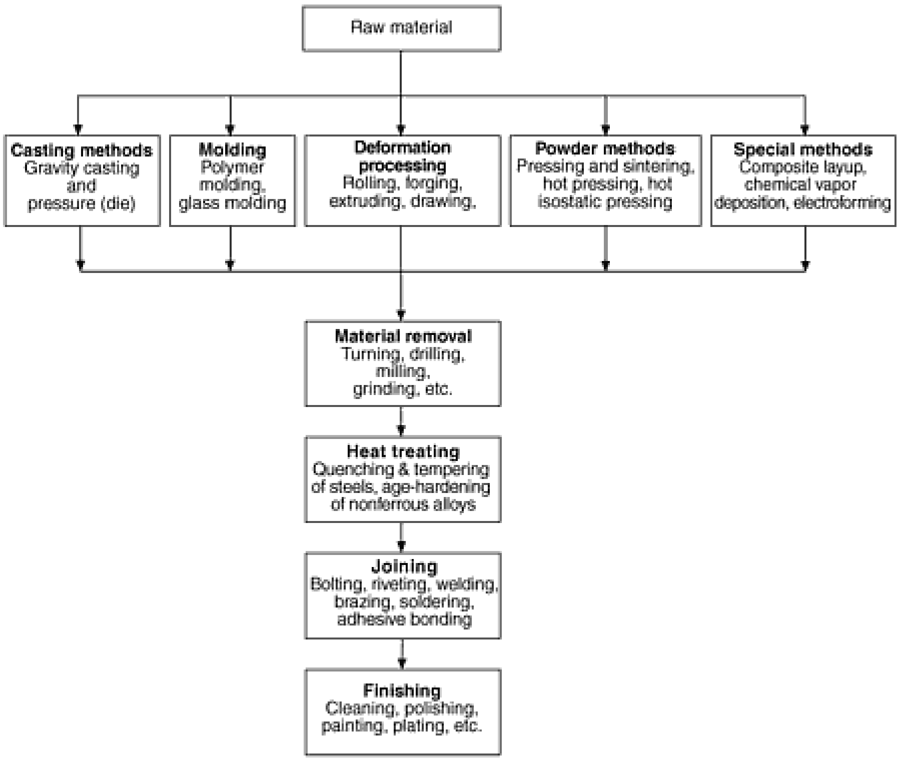
Raw material
Casting methods
Gravity casting and pressure (die)
Molding
Polymer molding, glass molding
Deformation processing
Rolling, forging, extruding, drawing,
Powder methods
Pressing and sintering, hot pressing, hot isostatic pressing
Special methods
Composite layup, chemical vapor deposition, electroforming
Material removal
Turning, drilling, milling, grinding, etc.
Heat treating
Quenching & tempering of steels, age-hardening of nonferrous alloys
Joining
Bolting, riveting, welding, brazing, soldering, adhesive bonding
Finishing
Cleaning, polishing, painting, plating, etc.

Fig. 4 The nine classes of manufacturing processes. The first row contains the primary forming (shaping) processes. The processes in the lower vertical column are the secondary forming and finishing processes. Source: Ref 2

In a very general sense, the selection of the material determines a range of processes that can be used to process parts from the material. Table 1 shows the manufacturing methods used most frequently with different metals and plastics (Ref 4). The material melting point and general level of deformation resistance (hardness) and ductility determine these relationships. The next aspect to consider is the minimum and maximum overall size of the part, often expressed by volume, projected area, or weight. Maximum size often is controlled by equipment considerations. Shape is the next factor to consider. The overall guide should be to select a primary process that makes the part as near to final shape as possible (near-net shape forming) without requiring expensive secondary machining or grinding processes. Sometimes the form of the starting material is important. For example, a hollow shaft can be made best by starting with a tube rather than a solid bar. Shape is often characterized by aspect ratio, the surface-to-volume ratio, or the web thickness-to-depth ratio. Closely related to shape is complexity. Complexity is correlated with lack of symmetry. It also can be measured by the information content of the part, that is, the number of independent dimensions that must be specified to describe the shape. Tolerance is the degree of deviation from ideal that is permitted in the dimensions of a part. Closely related to tolerance is surface finish. Surface finish is measured by the root-mean-square amplitude of the irregularities of the surface. Each manufacturing process has the capability of producing a part with a certain range of tolerance and surface finish (Fig. 5).

Table 1 Compatibility between materials and manufacturing processes

Process	**Cast iron**	**Carbon steel**	**Alloy steel**	**Stainless steel**	**Aluminum and aluminum alloys**	**Copper and copper alloys**	**Zinc and zinc alloys**	**Magnesium and magnesium alloys**	**Titanium and titanium alloys**	**Nickel and nickel alloys**	**Refractory metals**	**Thermoplastics**	**Thermoset plastics**
Casting/molding													
Sand casting	•	•	•	•	•	•	--	•	--	•	--	X	X
Investment casting	--	•	•	•	•	•	--	--	--	•	--	X	X
Die casting	X	X	X	X	•	--	•	•	X	X	X	X	X
Injection molding	X	X	X	X	X	X	X	X	X	X	X	•	--
Structural foam molding	X	X	X	X	X	X	X	X	X	X	X	•	X
Blow molding (extrusion)	X	X	X	X	X	X	X	X	X	X	X	•	X
Blow molding (injection)	X	X	X	X	X	X	X	X	X	X	X	•	X
Rotational molding	X	X	X	X	X	X	X	X	X	X	X	•	X
Forging/bulk forming													
Impact extrusion	X	•	•	--	•	•	•	--	X	X	X	X	X
Cold heading	X	•	•	•	•	•	--	--	X	--	X	X	X

Closed-die forging	X	•	•	•	•	•	X	•	•	--	--	X	X
Pressing and sintering (P/M)	X	•	•	•	•	•	X	•	--	•	•	X	X
Hot extrusion	X	•	--	--	•	•	X	•	--	--	--	X	X
Rotary swaging	X	•	•	•	•	--	--	•	X	•	•	X	X
Machining													
Machining from stock	•	•	•	•	•	•	•	•	--	--	--	--	--
Electrochemical machining	•	•	•	•	--	--	--	--	•	•	--	X	X
Electrical discharge machining (EDM)	X	•	•	•	•	•	--	--	--	•	--	X	X
Wire EDM	X	•	•	•	•	•	--	--	--	•	--	•	X
Forming													
Sheet metal forming	X	•	•	•	•	•	--	--	--	--	X	X	X
Thermoforming	X	X	X	X	X	X	X	X	X	X	X	•	X
Metal spinning	X	•	--	•	•	•	•	--	--	--	--	X	X

•, normal practice; --, less-common practice; X, not applicable.

Source: Adapted from Ref 4

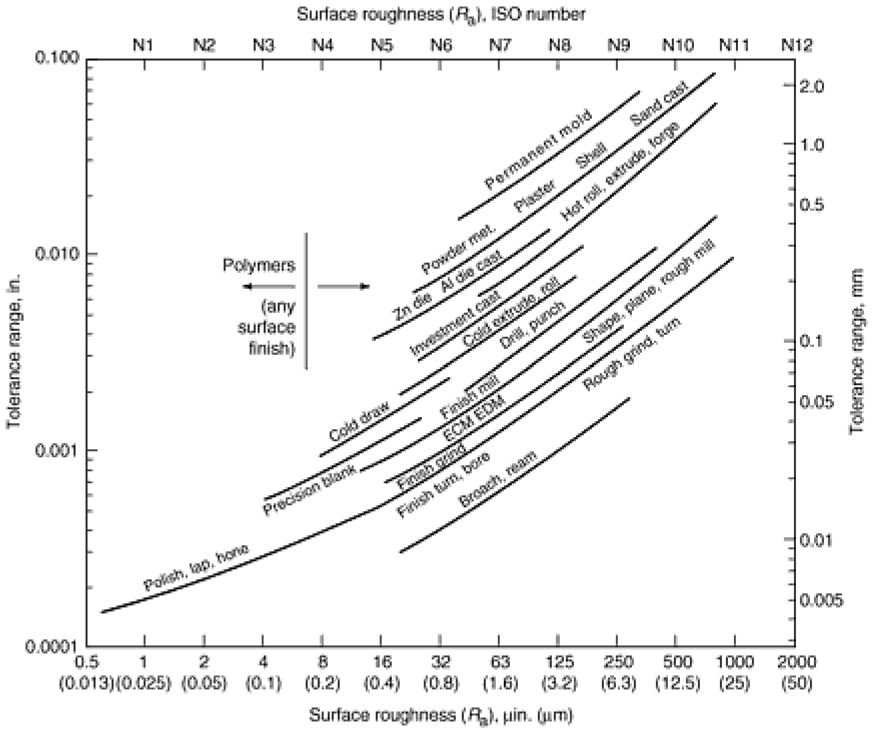

Fig. 5 Approximate values of surface roughness and tolerance on dimensions typically obtained with different manufacturing processes. ECM, electrochemical machining; EDM, electrical discharge machining. Source: Ref 5

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Concurrent Engineering

The selection of the material and its processing, product design, cost, availability, recyclability, and performance in final product form have become inseparable. As a result, more and more companies are forming multidisciplinary project teams to ensure that all needed input is obtained concurrently. This is reflected by the increasing use of "concurrent" or "simultaneous" engineering methods (Ref 6, 7).

Definition. As defined by the 1986 Institute for Defense Analysis Report R-338 (Ref 6), "concurrent engineering" is a "systematic approach to the integrated, concurrent design of products and their processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from concept through disposal, including quality, cost, schedule, and user requirements." Thus, concurrent engineering refers to the philosophic constructs needed to create a synergistic engineering environment that optimizes quality and productivity at a minimum cost.

Cross-Functional Design Teams. Today concurrent design proceeds through well-connected cross-functional integrated product development teams with a common purpose. Information exchange is critical to minimizing error and reducing the development time and costs. Given sufficient priority among a group of projects, an ideal team might be formed with individuals possessing historical, experimental, and fundamental knowledge in the candidate materials, processes, and products. The most effective design teams involve a clearly delineated group of individuals who work full time on the specified product from creation through market introduction. The team comprises not only research and development professionals, but also manufacturing and marketing members, and often members from quality, finance, or field service. When a team discovers holes in collective knowledge, it may need to rely in part on external sources of information and knowledge (e.g., from key suppliers), as well as to develop new information on its own. Consequently, information transfer both within the team and external to the team are important. References 8, 9, and 10 provide more detailed information on staffing cross-functional design teams and their effectiveness in the implementation of modern design practices and methods.

Concurrent Engineering Approach to Materials Processing (Ref 7). Figure 6 shows some of the concepts that must be addressed for successful concurrent material, process, and product engineering (in this case, for aluminum alloy manufacturing). Typical customer needs are indicated at the left and some typical processes are considered along the top of the figure. It is instructional to locate on this chart the specific types of processing efforts that are often pursued. Process refinement and process control both refer to improvements in a limited set of capabilities of a specific process. Unit process optimization refers to a more comprehensive improvement of the many facets of a particular processing operation. Alloy-process design refers to examining a range of sequential processes but limiting attention to a specific set of evolving product attributes, those with a microstructural origin in this case. Near-net-shape processing is one example of the more general case of eliminating process steps in order to reduce cost. Cost estimation deals with a specific process sequence and assumes that the desired product attributes are achievable.

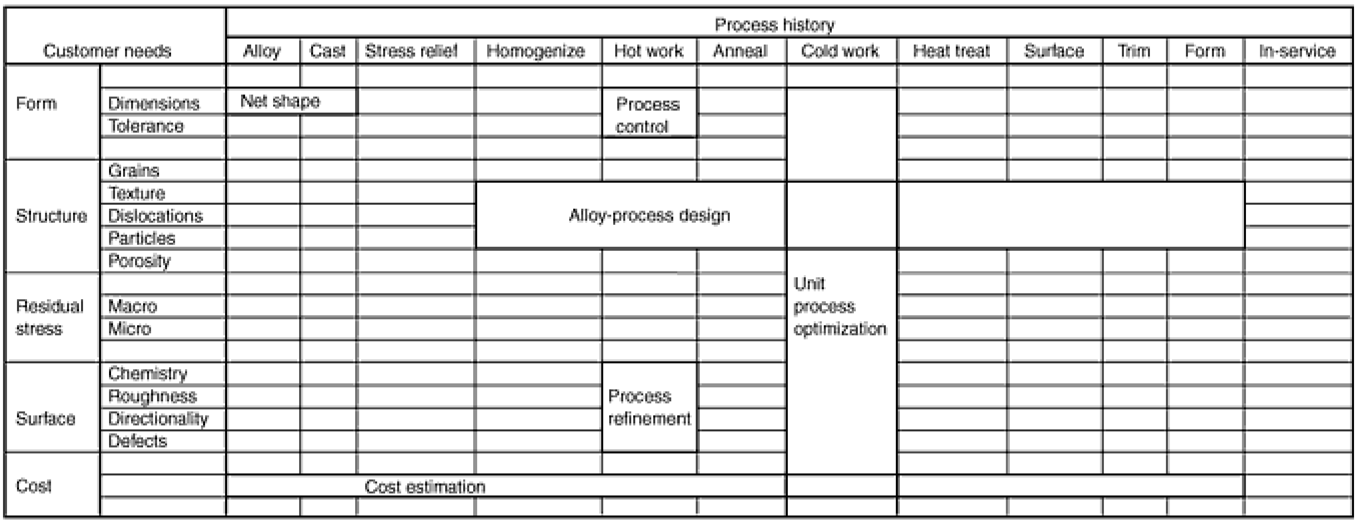
Customer needs
Process history
Alloy
Cast
Stress relief
Homogenize
Hot work
Anneal
Cold work
Heat treat
Surface
Trim
Form
In-service
Form
Dimensions
Tolerance
Structure
Grains
Texture
Dislocations
Particles
Porosity
Residual stress
Macro
Micro
Surface
Chemistry
Roughness
Directionality
Defects
Cost
Net shape
Process control
Alloy-process design
Unit process optimization
Process refinement
Cost estimation

Fig. 6 Concurrent engineering matrix for aluminum alloy manufacturing. Source: Ref 7

Some of these activities may require historical data (e.g., cost estimation), some may be experimental (e.g., alloy-process design), and some may be model based (e.g., process control). Different forms of information must, therefore, be dealt with in concurrent engineering to maximize knowledge transfer between individuals or subgroups. Improving the quantity, quality, and speed of knowledge transfer is essential because it can improve the effectiveness of the team in understanding and maneuvering within the design space outlined in Fig. 6. However, data transfer itself does not provide an increase in the team's design, optimization, or inverse engineering capabilities. Process modeling and computer simulations can provide such flexibility.

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Introduction

DESIGN FACTORS described in this article have been somewhat arbitrarily grouped into three categories: functional requirements, analysis of total life cycle, and other major factors; the factors are listed in Tables 1, 2, and 3, respectively. These categories intersect and overlap, which constitutes a major challenge in engineering design.

Table 1 Functional requirements in design

- **Performance specifications**
    - Definition of need
    - Risks and consequences of underspecification
    - Consequences of overspecification
- **Risk and hazard analysis**
    - Failure mode and effect analysis (FMEA)
    - Safety analysis
- **Design process/configuration**
    - Probabilistic or deterministic statistical approach
    - Stress or load considerations
    - Restrictions on size, weight, or volume
    - Service hazards, such as cyclic loading or aggressive environment
    - Failure anticipation
    - Reliability, maintainability, availability, and repairability
    - Quantity to be produced
    - Value analysis
    - Candidate materials and manufacturing processes
- **Design for manufacture and assembly (DFMA)**
- **Design for quality**
    - Robust design (Taguchi method)
    - Statistical process control (SPC)
    - Total quality management (TQM)
- **Reliability in design**
    - Quantitative determination
    - Reliability testing
- **Redesign**
    - Design review
    - Simplification and standardization
    - Functional substitution

Table 2 Total life cycle in design

- Material selection
- Producibility
- Durability
- Feasibility of recycling
- Design for recycling
- Energy requirements
  - For production
  - During use
  - For reclamation
- Environmental compatibility
  - Effect of product on environment
  - Effect of environment on product
- Inspection and quality-assurance testing
- Handling
- Packaging
- Shipping and storage
- Scrap value

Table 3 Other major factors in design

- **State of the art**
  - Prior knowledge
  - Possible patent infringement
  - Competitive products
- **Designing to codes and standards**
  - Codes for specific products, such as pressure vessels
  - Safety requirements
    - Products--Consumer Products Safety Commission
      - Warnings
      - Unintended uses
      - Labels
    - Manufacturing--Occupational Safety and Health Administration
    - Environmental requirements--Environmental Protection Agency
    - Industry standards
      - ANSI
      - ASTM
      - SAE
      - UL
      - ISO

Human factors/ergonomics

- Ease of operation
- Ease of maintenance

Aesthetics

Cost

Functional Requirements in Design

Performance Specifications

It is obvious that any design must necessarily meet performance specifications (Table 1). These specifications must reflect a full and complete analysis of the functions required of the product. An important distinction needs to be made between performance specifications, which enumerate the basic functional requirements of the product, and product specifications, which list requirements for configurations, tolerances, materials, manufacturing methods, and so forth. Performance specifications represent the basic parameters from which the design can be formulated; product specifications are codifications of designs, used for purchase or manufacture of the product. Excellence in design or product specification is not possible without complete and adequate performance specifications.

Performance specifications must reflect thorough consideration of the factors listed in Tables 2 and 3. Consequences and risks involved in possible product failures caused by predictable misuse or overload or by imperfections in workmanship or material must be considered in establishing performance specifications (see the discussion on "Risk and Hazard Analysis"). Situations in which the consequences of product failure would be dire or in which only the very lowest risks of failure can be tolerated dictate the use of stringent performance specifications. When product failure does not involve a risk of personal injury and is not likely to result in great financial loss to the user, economic considerations usually imply that performance specifications be no more stringent than necessary to meet functional requirements. Realistic performance specifications result in design and manufacture of products that perform their required functions with little risk of failure, and that at the same time can be produced at the lowest possible cost.

As an example of setting performance specifications to suit the application, resistance to corrosion can be specified at any of three levels: (a) avoiding contamination by corrosion products, (b) preventing leaks into or out of closed containers, and (c) maintaining structural integrity and other mechanical and physical properties in spite of corrosive attack. For food-processing equipment, the first of these considerations has paramount importance. For a bridge, the third factor is critical; furthermore, a bridge must retain its structural integrity for many years. In a petrochemical plant, all three considerations are important; chemical process equipment can be designed for continuous operation for two or three years, and any breakdown between scheduled maintenance periods would be extremely expensive. Furthermore, leakage of dangerous chemicals from process equipment is unacceptable. In this case, the cost of a breakdown and the damage caused by leakage can justify use of expensive materials if their performance reduces the probability of leaks or breakdown to very low levels. On an automobile body, low-carbon steel with a corrosion-resistant surface treatment and coating provides corrosion resistance consistent with the anticipated lifetime of the vehicle. Thus, for these various applications, the appropriate criteria for corrosion resistance depend on one or more of the following factors: the degree of contamination permitted by the application, the intended lifetime of the object, the corrosion characteristics of the environment, and the consequences and risks associated with corrosion failure.

Example 1: Functional Requirements for an Automotive Exhaust System.

The product design specification for the exhaust system must include the following functions:

- Conducting engine exhaust gases away from the engine

- Preventing noxious fumes from entering the automobile
- Cooling the exhaust gases
- Reducing the engine noise
- Reducing the exposure of automobile body parts to exhaust gases
- Affecting engine performance as little as possible
- Helping control undesirable exhaust emissions Having a service life that is acceptably long
- Having a reasonable cost, both as original equipment and as a replacement part

In its basic form, the exhaust system consists of a series of tubes that collect the gases at the engine and convey them to the rear of the automobile. The size of the tube is determined by the volume of the exhaust gases to be carried away and the extent to which the exhaust system can be permitted to impede the flow of gases from the engine. An additional device, the muffler, is required for noise reduction, and a catalytic converter is required to convert polluting gases to less-harmful emissions. The basic lifetime requirement is that the system must resist the attack of hot, moist exhaust gases for some specified period. In addition, the system must resist attack by the atmosphere, water, mud, and road salt. The location of the exhaust system under the car requires that it be designed as a complex shape that will not interfere with the running gear of the car, road clearance, or the passenger compartment. The large number of automobiles produced each year requires that the material used in exhaust systems be readily available at minimum cost.

This system requires numerous material property requirements. The mechanical property requirements are not overly severe: suitable rigidity to prevent excessive vibration and fatigue plus enough creep resistance to provide adequate service life. Corrosion is the limiting factor on life, especially in the cold end, which includes the resonator, muffler, and tail pipe. Several properties of unique interest, that is, where one or two properties dominate the selection of the material, are found in this system. These pertain to the platinum-base catalyst and the ceramic carrier that supports the catalyst. The majority of the tubes and containers that comprise the exhaust system were for years made of readily formed and welded low-carbon steel, with suitable coatings for corrosion resistance. With the advent of greater emphasis on automotive quality and longer life, the material selection has moved to specially developed stainless steels with improved corrosion and creep properties. Ferritic 11% Cr alloys are used in the cold-end components, with 17 to 20% Cr ferritic alloys and austenitic Cr-Ni alloys in the hot end of the system.

Risk and Hazard Analysis

As described briefly above, product failure and the associated risk of personal injury are critical considerations of the engineering design process. No engineering system/component devised or used can be 100% safe or error free. The objective of risk and hazard analysis is to identify the level of risk and to pinpoint the parts of the system that represent the greatest risk for failure. Then, if the analysis is used properly, steps can be taken to eliminate the cause or reduce the risk to an acceptable minimum. It has been demonstrated that hardware systems approaching a "failure-free" condition can be produced when actions are taken at all levels that are based on:

- Attention to past experiences with similar systems
- Availability of risk information for all project personnel
- A sound, aggressive risk and hazard analysis during all phases
- Development of suitable corrective action and safety programs based on the analysis
- A continuous and searching review of all phases of the program efforts

The various analysis techniques have developed from the search for system reliability. Consequently the approach is hardware oriented, with the emphasis on ensuring that hardware is able to perform its intended function.

Figure 1 is a flow chart that shows the integration of risk and hazard analysis in the overall design process. Even if designers or design managers are not directly responsible for implementing these analyses, they must be familiar with the methodology so that they understand how they are carried out and how they can respond in terms of design or system changes. Most efforts are best completed during early design phases, and they can be effectively used during design reviews to provide valuable feedback to the design to avoid failures.

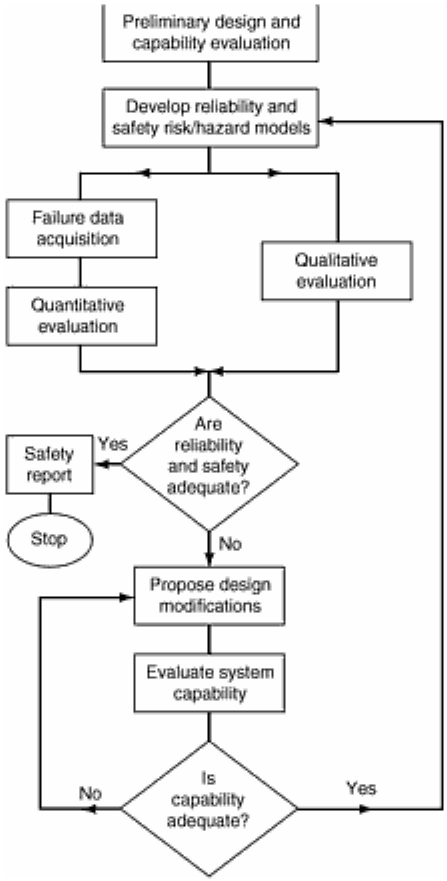
Preliminary design and capability evaluation
Develop reliability and safety risk/hazard models
Failure data acquisition
Quantitative evaluation
Qualitative evaluation
Are reliability and safety adequate?
Yes
Safety report
Stop
No
Propose design modifications
Evaluate system capability
Is capability adequate?
No
Yes

Fig. 1 Flow chart showing the integration of risk and hazard analysis into the design process. Source: adapted from Ref 1

Defining Risk. To clarify acceptable risk, Starr et al. (Ref 2) suggest it is useful to recognize the existence of four different definitions of "risk":

- *Real risk* is determined by actual circumstances as the future unfolds.
- *Statistical risk* is determined from currently available data, based on assumptions that a large number of future systems will, on the average, act the same way as a large number of similar past systems.
- *Predicted risk* is based on analysis of system, models, and historical data.
- *Perceived risk* is risk seen intuitively by individuals or society.

It should be noted that only "real risk" is a property of hardware. The other three risks represent the concept of risk represented by the system.

An important factor in the perception of risk is the probable severity of the consequences if an accident were to occur. A complete assessment of risk requires that the potential effects of an accident be integrated with a probability of its occurrence.

Linked closely to severity of consequences in the perception of risk is the episodic nature of consequences. It seems that the size of a potential accident is more important than the probability of occurrence. This truly represents society's value system to a great degree. Activities capable of producing catastrophic accidents, therefore, are seen as a great risk and must be more stringently controlled than high-frequency individual risks.

The two methodologies described later in this article can identify possible hazards and possibly identify the resources that are necessary to avoid or reduce the risks; however, whether the resources should be expended to alleviate the perceived risk remains a political-humanistic-management decision. The justification for undertaking these risk and hazard technological studies is that they give a clearer picture of decisions that must be made to ensure that the functional requirements of a design can be met. More detailed information on quantitative and qualitative risk and hazard analyses is found in Ref 3 and in the section "Human Factors and Safety in Design" in this article.

Failure mode and effect analysis (FMEA) was originally developed as a tool to review the reliability of systems and components. It has been modified over the years to include criticality analysis (CrA) and failure hazard analysis (FHA) to help determine equipment safety requirements. Its intent is still to ensure reliable system function. The objective of FMEA is to expose all potential element failure modes to scrutiny, to classify and quantify their possible causes with their associated probability of occurrence, and to evaluate their impact on the overall system performance.

Failure mode and effect analysis normally is implemented as part of a comprehensive reliability program. The analysis is performed at increasing levels of complexity as the design progresses, so that the recommendations resulting from the analysis can be implemented early at minimum cost. The results are used to guide other activities such as design, purchasing, manufacturing, and quality control.

Failure mode and effect analysis is a systematic, organized procedure for determining, evaluating, and analyzing all potential failures in an operating system; it is used to supplement and support other reliability or safety activities. The FMEA process involves examining each potential failure mode to assess if the system elements support reliability and to ascertain the consequences of the failure on the entire system. The general process involves the following steps:

1. The probable failure modes of the system are identified, evaluated, assessed, and documented.
2. The documentation of possible failure modes is used to check and verify the safety of the design.
3. Corrective actions are formulated to eliminate or reduce to an acceptable level the consequences of the failure.

The formal procedure (Fig. 2) for preparing an FMEA constitutes the following steps:

1. A functional block diagram or logic diagrams are developed for the system or subsystem. Copies of these diagrams become part of the FMEA documentation. Individual items to be considered are identified by number.
2. All realistic probable failure modes of each element on the diagram are postulated and entered on the FMEA documentation item by item.
3. The probable causes associated with each failure mode are listed beside each failure mode.
4. The immediate consequences of each assumed failure are described and listed beside the failure mode. Symptoms that would affect the function are also listed.
5. Any internal compensating provisions, within the system that either circumvent or mitigate the effect of the failure, are evaluated and noted.
6. The effect of the failure on other components or systems is evaluated and documented.
7. The level of severity of each mode of failure is evaluated in terms of importance and documented as critical, major, or minor.
8. A quantitative probability of occurrence of the failure mode is made. The probability should be expressed numerically (Ref 5), where possible. In some cases, categorizing may be more meaningful if commonly defined categories are used.
9. Finally, remarks and recommendations are documented. Here the analyst provides any additional meaningful data.

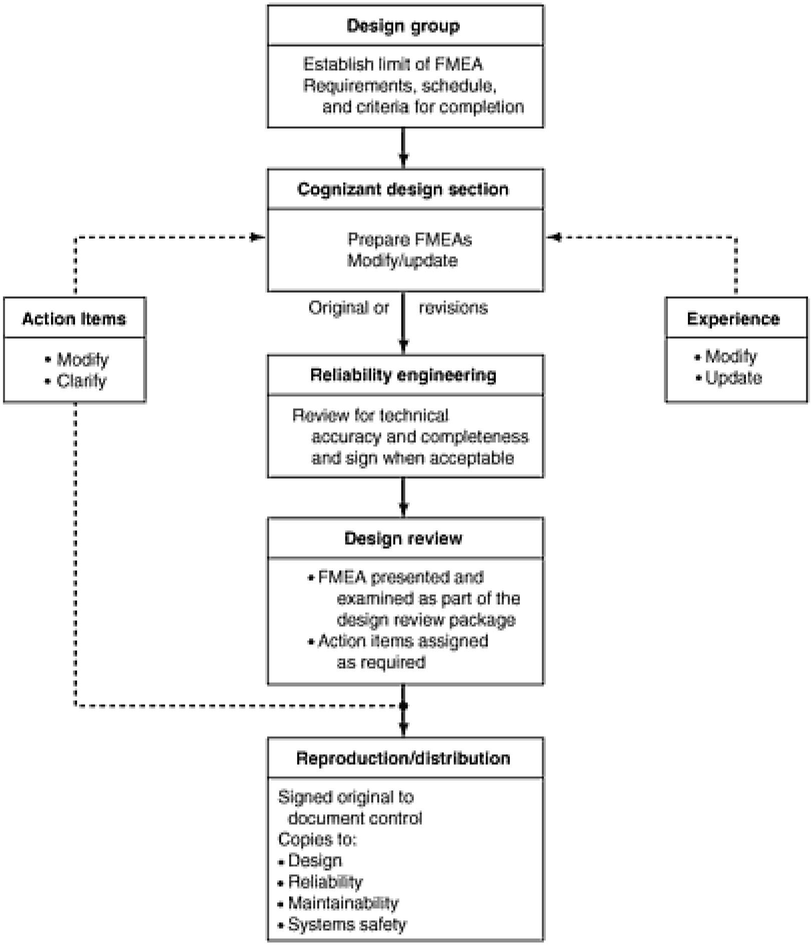
Design group
Establish limit of FMEA
Requirements, schedule, and criteria for completion
Cognizant design section
Prepare FMEAs
Modify/update
Action items
• Modify
• Clarify
Experience
• Modify
• Update
Original or revisions
Reliability engineering
Review for technical accuracy and completeness and sign when acceptable
Design review
• FMEA presented and examined as part of the design review package
• Action items assigned as required
Reproduction/distribution
Signed original to document control
Copies to:
• Design
• Reliability
• Maintainability
• Systems safety

Fig. 2 Failure mode and effect analysis flow chart. Source: Ref 4

Safety analysis is the synthesis of other risk/hazard analysis techniques to produce a qualitative systematic analysis throughout all phases of the project design, development, and implementation, with the objective of preventing accidents. This includes preventing personnel injuries, damage to equipment, and so forth. The techniques are simple but rigorous and time consuming, and to be effective must be continued throughout the life of the system from conception to shutdown and disposal. The method can be applied to any system but from a different point of view than system analysis. The focus of safety analysis is the prevention of hazardous failure.

The primary tools of safety analysis are worksheets, a hazard log book, a checklist of hazards, and a system description. A basic requirement is that the practitioners have a willingness to challenge the status quo; they cannot be the same as those committed to the design and implementation of the hardware system.

The identification of the hazards is an initial and continuous activity. Identification initiates an iterative process--the preliminary hazard analysis (Fig. 3) that undertakes elimination or reduction of the essential hazardous situations to an acceptable minimum. Design changes, safety devices, warning systems, crew procedures, emergency measures, and so forth, are all recommended. These are carried out to control or resolve the hazard situation. This often requires compromises between the designer and the safety analyst, or even changes in the specification governing the functions and use of the system. At the completion of the preliminary hazard analysis:

- The general hazards of concern are identified.
- Additional design and operation requirements have been established to forestall or alleviate anticipated hazards.
- Areas where further improvements with respect to safety are necessary have been identified.
- A databank has been started that can be used to follow and document potentially hazardous situations.

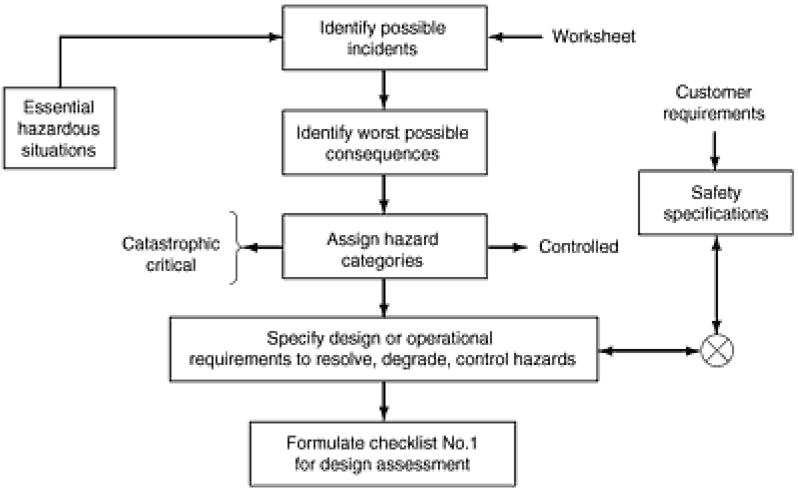
Identify possible incidents
Worksheet
Essential hazardous situations
Identify worst possible consequences
Customer requirements
Safety specifications
Catastrophic critical
Assign hazard categories
Controlled
Specify design or operational requirements to resolve, degrade, control hazards
Formulate checklist No.1 for design assessment

Fig. 3 Safety analysis flow chart for preliminary hazard analysis. Source: Ref 6

Because no system is perfect, safety analysis cannot stop with the design and production of hardware. The safety analysis evolves into the next stage, operating hazard analysis (OHA) (Fig. 4). This serves to identify solutions where failure that is attributable to operator performance is likely to occur. The techniques of carrying out OHA are the same as for system hazard analysis except that the human operator and his limitations must be considered. The outputs from OHA are operational requirements that compensate for or correct a human limitation. The procedures have to either prevent the hazard or confine and minimize its impact.

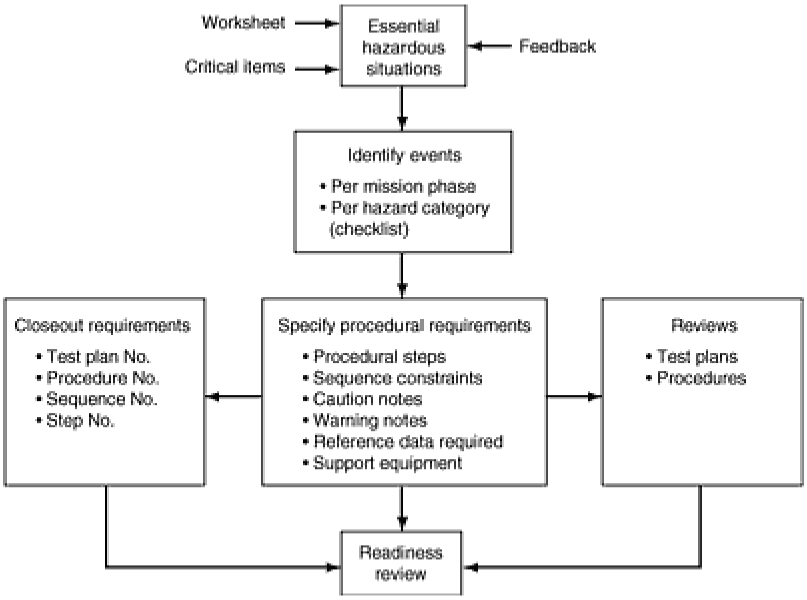
Worksheet
Critical items
Essential hazardous situations
Feedback
Identify events
• Per mission phase
• Per hazard category (checklist)
Closeout requirements
• Test plan No.
• Procedure No.
• Sequence No.
• Step No.
Specify procedural requirements
• Procedural steps
• Sequence constraints
• Caution notes
• Warning notes
• Reference data required
• Support equipment
Reviews
• Test plans
• Procedures
Readiness review

Fig. 4 Safety analysis flow chart for operating hazard analysis. Source: Ref 6

The outputs from OHA can be in the form of procedural steps, sequence constraints, caution or warning notes, reference data, or support or standby equipment.

The Design Process

The design process includes determination of the configuration of the product and various component parts and selection of materials and processes to be used. In its early stages, the process consists of evaluating various combinations of preliminary configuration, candidate material and potential method of manufacture, and comparing these with previously established performance specifications. The relationship between configuration and material (processed in some specific way) is that every configuration places certain demands on the material, which has certain capabilities to meet these demands. A common specific relationship is a relationship between the stress imposed by the configuration and the strength of the material. Of course, there are other relationships as well. Changes in processing can change the properties of a material, and certain combinations of configuration and material cannot be made by some manufacturing processes.

Probabilistic or Deterministic Approach. Quantitative relationships between configurational demands and material capabilities can be established by deterministic methods--the more well known approach--or probabilistic methods. In the former, nominal or average values of stress, dimension, and strength are used in design calculations; appropriate safety factors are used to compensate for expected variations in these parameters and for discontinuities in the material. In the probabilistic approach, each design parameter is accorded a statistical distribution of values. From these distributions and from an allowable limit on probability of failure, minimum acceptable dimensions in critical areas (or minimum strength levels for critical components) can be calculated. Compared with deterministic methods, the probabilistic approach requires greater sophistication on the part of the designer and more elaborate calculations, but offers the potential for more compact parts that use less material. A significant handicap to use of probabilistic methods is the fact that statistical distributions of properties are not widely available and often must be determined before these methods can be applied to a specific design problem.

In either approach to design, the effects of notches and stress concentrations must be considered, because these features increase the vulnerability of all types of parts to failure. However, studies in fracture mechanics have shown that, under some circumstances, notches and discontinuities in the material may be benign, and therefore of little consequence in some design applications. A more detailed description on the use of statistical methods for the prediction of such factors as operating stress, strain, deflection, deformation, wear rate, fatigue strength, creep strength, or service life is found in the Section "Statistical Aspects of Design."

Effect of Service Hazards. Cyclic loading, use at extreme temperatures, and the presence of agents that cause either general corrosion or stress-corrosion cracking are special hazards that must be considered during the materials-selection process. Table 4 lists some common failure modes and the mechanical properties most related to particular modes. Cyclic loading, in particular, is a very common factor in the design of anything that has moving parts; it is also widely recognized that fatigue is responsible for a large portion of all service failures. In 1943, Almen (Ref 7) made an observation that is still valid about fatigue:

> "Fully 90 percent of all fatigue failures occurring in service or during laboratory and road tests are traceable to design and production defects, and only the remaining 10 percent are primarily the responsibility of the metallurgist as defects in material, material specification, or heat treatment.
>
> "Study of fatigue of materials is the joint duty of metallurgical, engineering, and production departments. There is no definite line between mechanical and metallurgical factors that contribute to fatigue. This overlapping of responsibility is not sufficiently understood.
>
> "Hence, the engineers are constantly demanding new metallurgical miracles instead of correcting their own faults. Until metallurgists are less willing to look for metallurgical causes of fatigue and insist that equally competent examination for mechanical causes be made, we cannot hope to make full use of our engineering material."

Table 4 Relationships between failure modes and material properties

Failure mode	**Material property**														
	Ultimate tensile strength	**Yield strength**	**Compressive yield strength**	**Shear yield strength**	**Fatigue properties**	**Ductility**	**Impact energy**	**Transition temperature**	**Modulus of elasticity**	**Creep rate**	K_{Ic} **(a)**	K_{Iscc} **(b)**	**Electrochemical potential**	**Hardness**	**Coefficient of expansion**
Gross yielding		X		X											
Buckling			X						X						
Creep										X					
Brittle fracture							X	X			X				
Fatigue, low cycle					X	X									
Fatigue, high cycle	X				X										
Contact fatigue			X												
Fretting			X										X		
Corrosion													X		
Stress-corrosion	X											X	X		

cracking															
Galvanic corrosion													X		
Hydrogen embrittlement	X														
Wear														X	
Thermal fatigue										X					X
Corrosion fatigue					X								X		

An "X" at the intersection of material property and failure mode indicates that a particular material property is influential in controlling a particular failure mode.

(a) Plane-strain fracture toughness.

(b) Threshold stress intensity to produce stress-corrosion cracking

Although Almen spoke specifically about fatigue, his comments can be applied to engineering design on a far broader basis. His comments must not be construed to excuse materials engineers from a proper share of the overall design responsibility, nor to allow them to slacken their efforts to find better materials for specific applications.

Almen's comments do imply that all aspects of design must be considered, because even apparently insignificant factors can have far reaching effects. (For example, there is at least one known instance in which fatigue failure of an aircraft in flight was traced to an inspection stamp that was imprinted on a component using too heavy a hammer blow.)

Failure Anticipation. Even parts for which loading in service is known accurately and stress analysis is straightforward, gross design deficiencies can arise from reliance on static load-carrying capacity based solely on tensile and yield strengths. The possibility of failure in other modes, such as fatigue, stress-corrosion cracking, and brittle fracture caused by impact loading, must be considered in the design process.

Any discussion of potential failures in service should include careful consideration of the possible consequences of failure. Those failure modes that might endanger life or limb, or destroy other components of the apparatus, should be avoided. Sometimes, a piece of equipment is designed so that one component will fail in a relatively harmless fashion and thus avoid the potentially more serious consequences of the failure of another. For example, a piece of earth-moving equipment might be designed so that the engine will stall if the operator attempts to lift a load so heavy that it might upset the equipment or damage any of the structural components. A blowout plug in a pressure vessel is another example. Conformance to codes and standards, such as those listed in Table 3, can preclude serious consequences of service failure, but designers still must exercise careful judgment in studying (and designing against) the consequences of possible modes of failure.

Restrictions on Size, Weight, or Volume. The size and weight of a part can affect the choice of both material and manufacturing process. Small parts often can be economically machined from solid bar stock, even in fairly large quantities. The material cost of a small part may be far less than the cost of manufacturing it, perhaps making relatively expensive materials feasible. Large parts can be difficult or impossible to heat treat to high-strength levels. There are also limits on size for parts that can be formed by various manufacturing processes. Die castings, investment castings, and powder metallurgy parts are generally limited to a few kilograms. When weight is a critical factor, parts often are made from materials having high strength-to-weight ratios.

The quantity of parts to be made can affect all aspects of the engineering design process. Low-quantity production runs can seldom justify the investment in tooling required by production processes, such as forging or die casting, and may limit the choice of materials to those already in the designer's factory or those stocked by service centers. High-quantity production runs may be affected by the capability of materials producers to supply the required quantity. Mass-produced parts sometimes are designed and redesigned, requiring a large expenditure for engineering and evaluation, but providing enough savings, considering the large quantity involved, to make the effort worthwhile. Design for small-quantity parts may be limited to finding the first design and material that serve the required purpose.

Other Relationships Influencing the Design Process. Products that can be manufactured in several locations can present additional problems for designers because the cost and availability of materials can vary from place to place. If the product is to be made in different countries, the nearest equivalent grades of steel, for example, might be different enough to affect service performance. In some areas that have low prevailing labor costs, it may be desirable to design a labor-intensive product; in a high-cost labor market, the designer often attempts to design the product to fit the capabilities of automated manufacturing equipment.

It is relatively late in the design process before designers, materials engineers, and manufacturing engineers, by working together, can establish those factors described in "Factors in Material Selection" (for example, Table 1 in the previously mentioned article). Only then can the field of candidate materials and manufacturing processes be narrowed to a manageable number of alternatives. The implications of each of these alternative materials and manufacturing processes can then be evaluated, and any required changes in configuration can be made.

One of the complicating factors in materials selection is that virtually all materials properties, including fabricability, are interrelated. Substituting one material for another, or changing some aspect of processing in order to effect a change in one particular property, generally affects other properties simultaneously. Similar interrelations that are more difficult to characterize exist among the various mechanical and physical properties and variables associated with manufacturing processes. For example, cold drawing a wire to increase its strength also increases its electrical resistivity. Steels that have high carbon and alloy contents for high hardenability and strength generally are difficult to machine and weld. Additions of alloying elements such as lead to enhance machinability generally lower long-life fatigue strength and make welding and cold forming difficult. The list of these relationships is nearly limitless.

Value analysis also known as value engineering, is a problem-solving methodology that focuses on identifying the key function(s) of a design so that unnecessary costs can be removed without compromising the quality of the design. Key concepts that must be examined during value analysis include:

- Is it necessary?
- Does it do more than is required?
- Does it cost more than it is worth?
- Is there something that does the job better?
- Can it be made by a less-costly method?
- Can a standard item be used?
- Considering the quantities used, could a less-costly tooling method be used?
- Does it cost more than the total of reasonable labor, overhead, material, and profit?
- Can another manufacturer provide it at less cost without affecting dependability?
- If it was a personal purchase, would the item be too expensive to purchase?

Value analysis using such criteria can provide both designers and managers with assurance that the final combination of configuration, material, and manufacturing process is a good combination. More detailed information on this topic is found in Ref 8.

Design for Manufacture and Assembly

With increased awareness of the importance of the interaction between design and manufacture, a new field aimed at formalizing this relationship is evolving, called "design manufacture and assembly" (DFMA) (Ref 9). The DFMA approach examines the product design in all aspects for methods of integrating the product and its processing so that the best match is made between product and process requirements and that the integrated product/process ensures inherent ease of manufacture. A major objective of DFMA is to ensure that the product (including material selection) and the process are designed together.

Figure 5 summarizes the steps taken when using DFMA analysis during design. The design-for-assembly (DFA) analysis is conducted first, leading to a simplification of the product structure. Then, early cost estimates for the parts are obtained for both the original design and the new design to make trade-off decisions. During this process, the best materials and processes to be used for the various parts are considered. For example, would it be better to manufacture a cover from plastic or sheet metal? Once the materials and processes have been finally selected, a more thorough analysis for design for manufacture (DFM) can be carried out for the detail design of the parts.

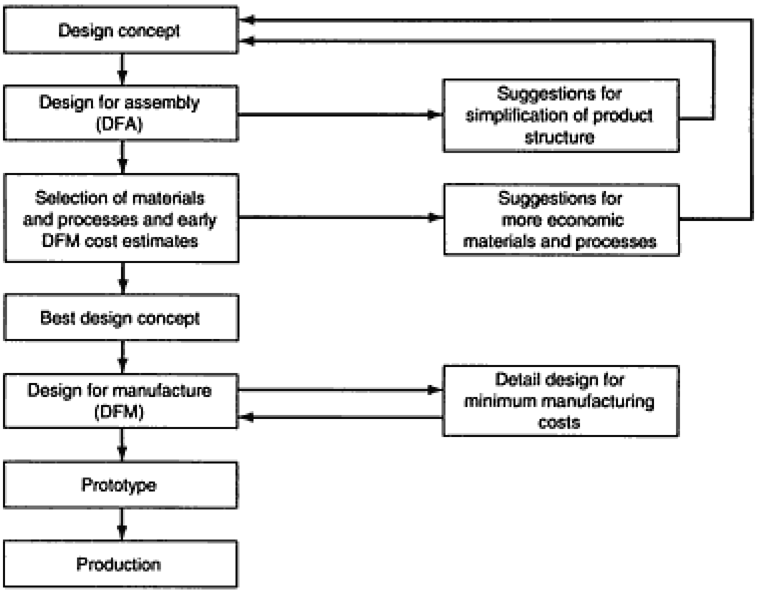
Design concept
Design for assembly (DFA)
Suggestions for simplification of product structure
Selection of materials and processes and early DFM cost estimates
Suggestions for more economic materials and processes
Best design concept
Design for manufacture (DFM)
Detail design for minimum manufacturing costs
Prototype
Production

Fig. 5 Typical steps taken when using design for manufacture and assembly (DFMA) analysis during design

Reducing the number of separate parts, thereby simplifying the product, is the greatest improvement provided by DFA (Ref 10). To give guidance in reducing the part count, the DFA software asks the following questions as each part is added to the product during assembly:

- Is the part or subassembly used only for fastening or securing other items?
- Is the part or subassembly used only for connecting other items?

If the answer is "yes" to either question, the part or subassembly is not considered theoretically necessary. If the answer is "no" to both questions, the following criteria questions are considered:

- During operation of the product, does the part move relative to all other parts already assembled?
- Must the part be made from a different material than, or be isolated from, all other parts already assembled? Only fundamental reasons concerned with material properties are acceptable.
- Must the part be separate from all other parts already assembled because the necessary assembly or disassembly of other separate parts would otherwise be impossible?

If the answer to all three criteria questions is "no," the part cannot be considered theoretically necessary.

Implementation of DFM analysis helps to quantify cost of parts and allow trade-off decisions to be made for design proposals and material and process selection. Major cost savings are achieved when:

- The design of products, subassemblies, components, modules, and individual parts are standardized
- Readily processed materials are used
- The product design is developed for the particular manufacturing process that will be used to make the part
- Each part is designed for ease of manufacture
- Inherently expensive machining operations are eliminated

Of course, engineering designers must design products that not only can be economically manufactured and assembled, but they also must function as intended. This requires selecting and understanding the physical principles by which the product will operate. Moreover, proper function requires special attention to tolerances. These two considerations are called designing for function and fit. However, designers must consider a myriad of other issues as well: installation, maintenance, service, environment, disposal, product life, reliability, safety, and other issues. The phrase "design for X" (DFX) refers to these other issues (Ref 11).

Designing for DFM, DFA, minimum parts, function, fit, and DFX is still not all that is required of the engineering designer. Products also must be designed for marketing and profit, that is, for the customer and for the nature of the marketplace. Designers, therefore, need to be aware of what features customers want, and what customers consider to be quality in a product. In addition, marketing considerations should include cost, quality, and, increasingly important, time--that is, when the product will reach the marketplace.

Designers also should recognize that the processes by which parts and products are made, and the conditions under which they are used, are variable. As described in the section on "Design for Quality," designing so that products are robust under these variabilities is another design requirement.

Design for Quality

Robust Design. Variability is the enemy of manufacturing. It is a major cause of poor quality resulting in unnecessary manufacturing cost, product unreliability, and ultimately, customer dissatisfaction and loss of market share. Variability reduction and robustness against variation of hard-to-control factors are therefore recognized as being of paramount importance in the quest for high-quality products. In a design for quality approach, the design team seeks to design the product and process in such a way that variation in hard-to-control manufacturing and operational parameters is minimal. The ideas behind this approach are largely attributable to the efforts of Genichi Taguchi and the cost-saving approaches to quality control pioneered in Japan. The Taguchi method(s), also known as *robust design,* is an integrated system of tools and techniques that allow engineers and scientists to reduce product or process performance variability while simultaneously guiding that performance toward the best possible level. Major robust design techniques, tools, and concepts include the quality loss function, parameter design, tolerance design, signal-to-noise ratio, technology development, and orthogonal arrays. Each of these are treated extensively in the literature (see, for example, Ref 12 and 13).

Statistical Process Control. Another important tool for quality improvement, advocated by W.E. Deming (Ref 14, 16), and Scherkenbach (Ref 15), is *statistical process control* (SPC). This is a procedure, using statistical mathematics, which signals that some extraneous factor is affecting the output of a production process. The signal alerts production and quality personnel that a process fault should be looked for and eliminated. In this way, the procedure aids in identifying and correcting the causes of product component defects. Because there are natural random variations in the results of any manufacturing process, the ability to differentiate between these random variations and those caused by some change in process conditions is a critical part of maintaining good control over specified characteristics and dimensions. Broken or worn cutting tools, slipped adjustments, leaks in a pressurized system, and an accidental change to a less-active solder flux are some examples of the kinds of process changes that might otherwise not be noticed, but which may cause a quality deterioration that would be detected by *SPC* analyses. Additional information about SPC is provided throughout this Handbook.

Total Quality Management. Deming also states that 85% of quality problems are caused by systems, procedures, or management, and only 15% of quality problems are caused by bad workmanship (Ref 16). Blaming workers is not the way to cure quality problems. Incidentally, the 85% of quality problems attributable to management includes problems traceable to weaknesses or errors in the product design.

Current thinking on the best managerial approaches to control quality improvement involve heavy worker participation in both the monitoring of quality and the corrective actions taken to solve quality problems. One approach that encompasses worker involvement is *total quality management* (TQM). Total quality management is more a broad management philosophy and strategy than a particular technique. Referred to earlier as total quality control, it originated in Japan. It involves:

- A strong orientation toward the customer in matters of quality.
- Emphasis on quality as a total commitment for all employees and all functions including research, development, design, manufacturing, materials, administration, and service. Employee participation in

quality matters is standard at all levels. Suppliers also participate.

- A striving for error-free production. Perfection is the goal.
- Use of statistical quality control data and other factual methods rather than intuition to control quality.
- Prevention of defects rather than reaction after they occur.
- Continuous improvement.

Total quality management programs usually stress that quality must be designed into the product rather than tested for at the end of the production process. Reference 17 provides additional information.

Reliability in Design

Definition. Reliability is a measure of the capacity of equipment or systems to operate without failure in the service environment. The National Aeronautics and Space Administration (NASA) defines reliability as the probability of a device performing adequately for the period of time intended under the operating conditions encountered. Reliability is always a probability, thus its calculation is one form of applied mathematics. Probabilistical and statistical methods, however, like any other forms of mathematics, are aids to, not substitutes for, logical reasoning.

Reliability is identified with a state of knowledge, not a state of things. Reliability cannot be used to predict discrete, or individually specific, events; only probabilities, that is averages, are predicted. Probability is a measure of what is expected to happen on the average if the given event is repeated a large number of times under identical conditions. Probability serves as a substitute for certainty. A generalization is made from samples, and the conclusions reached cannot be considered to be absolutely correct.

The NASA definition of reliability (and any other definition) includes "adequate performance" of the specific device. There is no general definition of adequate performance. Criteria for adequate performance must be carefully and exactly detailed or specified in advance for each device or system considered.

A reliability of 0.99 implies a probability of 1 failure per 100. A reliability of 0.999 does not imply greater accuracy (one more significant figure) but an order of magnitude difference, that is, a probability of failure of 1 per 1000.

Reliability Tasks. All general definitions, like the NASA definition, are qualitative. A quantitative definition of reliability for operating time t is:

$$R(t) = P(T > t) \qquad \textbf{(Eq 1)}$$

where R is reliability, P is probability, and T is the time to failure of the device. (T itself is a variable.)

The first task in ensuring reliability is to derive and investigate Eq 1. This is first done for a single component. The reliability of an entire system is then determined in keeping with the functions and configuration of the units composing the system. This, in turn, can be a subsystem of a more complex system. The building process continues until the entire system has been treated. The complete system can be so complex that it includes entire organizations, such as maintenance and repair groups with their personnel.

The second task, after the system and its reliability are truly understood, is to find the best way of increasing the reliability. The most important methods for doing this are:

- Reduce the complexity to the minimum necessary for the required functions. Nonessential components and unnecessary complexity increase the probability of system failure, that is, they decrease reliability.
- Increase the reliability of components in the system.
- Use parallel redundancy, one or more "hot" spares operate in parallel. If one fails, others still function.
- Use standby redundancy. One or more "cold" spares is switched to perform the function of a failed component or subsystem.
- Employ repair maintenance. Failed components are replaced by a technician rather than switched in as with standby redundancy. Replacement is neither automatic nor necessarily immediate.

- Employ preventive maintenance. Components are replaced periodically by new components even though they may not have failed prior to the time of replacement.

The third task is to maximize system reliability for a given weight, size, or cost. Conversely, the task may be to minimize weight, size, cost or other constraints for a given reliability.

Graphic Representation of Reliability. Consider a population of homogeneous components from which a very large sample is taken and placed in operation at time $T = 0$. (T is age, in contrast with t, commonly used for operational life or mission time.) The population will initially show a high failure rate. This decreases rapidly as shown in Fig. 6. This period of decreasing failure rate is called various names, such as early life period, infant mortality period, and shakedown period. Failure occurs due to design or manufacturing weaknesses, that is, weak or substandard components.

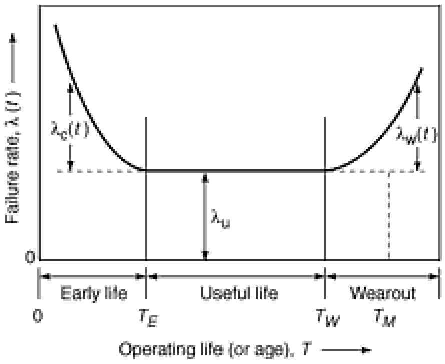

Fig. 6 Mortality curve; failure rate versus age (schematic). Source: Ref 18

When the substandard components have all failed at age T_E, the failure rate stabilizes at an essentially constant rate. This is known as useful life because the components can be used to greatest advantage, Failures during useful life are known as random, chance, or catastrophic because they occur randomly and unpredictably.

When components reach age T_W, the failure rate again increases. Failures begin to occur from degradation due to aging or wear as the components are approaching their rated life.

Early life can be made as short as desired (even eliminated) by proper design, fabrication and assembly, and/or deliberate burn-in periods. For systems that must operate satisfactorily over extended periods, incidence of wear out can be postponed almost indefinitely by replacing units as they fail during useful life and replacing each unit (even if it has not failed or given any indication of imminent failure) no later than at the end of useful life. Reference 19 provides more detailed information on estimating useful life, mean time to failure, and mean time between failures.

Reliability Testing. Reliability tests measure or demonstrate the ability of equipment to operate satisfactorily for a prescribed time period under specified operating conditions. Assuming a system with ten components in series, which must operate for 1000 h with a reliability of 0.99, the characteristic life of a component must be $\sim 10^6$ h, or about 115 years. To obtain a state of knowledge to determine this requires more than 115 years of failure-free testing (115 components for 1 year or 1150 components for 6 weeks) for each of 10 components. If the number of parts is several hundred and the desired reliability is 0.999 (not at all uncommon), it is obvious that the required number of tests becomes absurdly impossible. Yet, such products are designed, built, and meet guaranteed performance.

Although maximum use is made of past performance data and engineering judgment, it is essential for the designer to know as soon as possible if a design objective for reliability and/or life will be met. To meet a production schedule, it is rarely realistic to test under normal operating conditions. Thus accelerated testing is desired. Three factors control the degree of acceleration: environment, sample size, and testing time. Environment includes any operating condition to which the part is subjected and that may affect its performance and/or durability. Two broad categories of testing are implied: (a) tests to determine which aspects of the environment are truly significant and (b) accelerated tests to determine performance as quickly as possible.

Univariate testing (one parameter at a time) for environmental factors is not always useful because there is no indication of any effect of interaction between two or more factors.

Factorial experiments can be used to estimate the main (direct) effect of each "stress," interactions between two (or more) stresses, and experimental error (Ref 20, 21, 22, 23, 24). Related information is contained in the Section "Statistical Aspects of Design," which is contained below.

To run a complete factorial experiment, especially for replication, may require a very large number of individual tests or runs. Fortunately, in such a situation, most of the desired information can be obtained by performing only a fraction of the full factorial. In one unusual (and outstanding) situation with 19 variables, a complete full factorial study would have required more than 500,000 samples. A judiciously selected fractional factorial design provided the desired information from a study of only 20 samples (Ref 20, 21, 22, 23, 24, 25).

Accelerated testing, which is reducing the time required for testing, can be accomplished by: (a) taking a large sample and testing only part of the sample to failure, (b) magnifying the stress, or (c) sudden-death testing. Alternatives (a) and (c) are especially useful in testing a large number of relatively inexpensive components. Sequential testing is more useful when there are only a few relatively expensive units.

If a number of identical units are tested simultaneously, failure will occur in an ordered sequence with the weakest units failing first, and so forth. Such ordering is unique with life testing (Ref 26). The choice of a test involving failure of r units out of n ($n > r$) rather than the choice of a test involving failure of r out of r units will, in general, permit determination of an estimate of characteristic life in a relatively shorter time. For example, if 20 units have to be operated for 200 h to induce all 20 failures, then on the average, only 46 h are needed to observe the first 10 failures in a sample of 20.

Use of magnified loading does reduce testing time and possibly the number of items required for the test. Correlation is a major problem because "normal" needs to be defined and enough overload data must exist to correlate with normal. Rabinowicz et al. (Ref 27) suggested a technique based on cumulative damage. An example of acceleration in fatigue testing was developed by Conover et al. (Ref 28). Intensified loading of programmed fatigue tests developed from field data was used to reduce time to failure in steels for automotive components by a factor of ten. These results were applicable for unnotched specimens, notched specimens, and automotive components.

Other useful reliability tests include sudden-death testing (Ref 18, 21), which is especially useful with a large number of relatively inexpensive units, and sequential testing (Ref 18, 21) which is especially useful for tests of a small number of relatively expensive units.

Redesign

Redesign often can improve performance and reduce cost, and can occur informally during the early stages of design. It may also result from formal design-review procedures. Failure-mode analysis is particularly useful in redesign to reduce the likelihood of further failures. These techniques often have resulted in greatly improved product performance.

Standardization and simplification of design can lead to substantial savings without loss of performance. Retaining only the most efficient sizes, types, grades and models of a product is an example; during World War II, the number of "standard" types of steel, brass, and bronze valves in the United States was reduced from 4080 to 2500. Utilization of standard off-the-shelf components can also lead to significant savings. It might be less costly, for example, to use a $\frac{1}{4}$-20 bolt 2 in. (50 mm) long, which is a widely stocked size, even though design requirements could be satisfied by a bolt $1\frac{7}{8}$ in. (48 mm) long, which would probably be a special order item.

Further savings could be realized if the assembly were to be redesigned to allow use of $1\frac{1}{2}$ in. (38 mm) or $1\frac{3}{4}$ in. (44 mm) bolts.

Functional substitution offers great opportunity for improvement and cost reduction through redesign. The goal of functional substitution is to find a new and different way to meet a design requirement. For example, a bolted assembly might be redesigned for assembly by welding, by pressing mating parts together, or by adhesive bonding. The scope of a functional redesign program might be rather modest, as in the example just mentioned, or it might entail complete redesign of the product.

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Statistical Aspects of Design

For many years engineers have designed components and structures using best available estimates of material properties, operating loads, and other design parameters. Once established, most of these estimated values have commonly been treated as fixed quantities or constants. This approach is called deterministic, in that each set of input parameters allows the determination of one or more output parameters, where those output parameters may include a prediction of factors such as operating stress, strain, deflection, deformation, wear rate, fatigue strength, creep strength, or service life. In reality, virtually all material properties and design parameters exhibit some statistical variability and uncertainty that influence the adequacy of a design.

Fundamentally, designing to prevent service failures is a statistical problem. In simplistic terms, an engineered component fails when the resistance to failure is less than the imposed service condition. Depending on the structure and performance requirements, the definition of failure varies; it could be buckling; permanent deformation; tensile failure; fatigue cracking; loss of cross section due to wear, corrosion; erosion; or fracture due to unstable crack growth. In any of these cases, the failure resistance of a large number of components of a particular design is a random variable, and the nature of this random variable often changes with time. The imposed service condition for these components is also a random variable; it too can change with time. The intersection of these two random variables at any point in time represents the expected failure percentage and provides a measure of component reliability.

This section presents some of the statistical aspects of design from an engineer's perspective. Some statistical terms are clarified first because many engineers have not worked in the field of statistics enough to put these terms into day-to-day engineering practice. More detailed information pertaining to the statistical aspects of design is found in Ref 29, 30, 31, 32, 33 and in Volume 8, *Mechanical Testing,* of the *ASM Handbook.*

Classification of Statistical Terms

Random Variables. Any collection of test coupons, parts, components, or structures designed to the same set of specifications or standards will exhibit some variability in performance between units. Performance can be measured by a wide variety of parameters, or some combination of those parameters. as discussed earlier. In any case, these measures of performance are not controlled, although there is often an attempt to optimize them to maximize performance, within prescribed cost constraints. Because these measures of performance are not controlled and subject to inherent random variability, they are commonly called random variables.

The tensile strength of a structural material is a practical example of a random variable. Given a single heat and lot of a material manufactured to a public specification, such as an ASTM, SAE/AMS, or Department of Defense (DoD) specification, repeated tests to determine the tensile strength of that material will produce varied results. This will be true even if the individual tests are performed identically, within the limits of engineering accuracy. Table 5 illustrates that even apparently similar tensile samples tested under identical conditions generally do not produce the same results, producing data scatter or variability. Each observation was based on randomly selected samples from each heat of material.

Table 5 Results of a hypothetical test series to determine the ultimate tensile strength of two heats of material

Sample No.	Tensile strength			
	Heat 1		Heat 2	
	MPa	ksi	MPa	ksi
1	522	75.7	517	75.0
2	511	74.1	490	71.1
3	489	70.9	499	72.4
4	554	80.3	514	74.6
5	500	72.5	503	72.9

Density Functions. In statistical terms, a density function is simply a function that shows the probability that a random variable will have any one of its possible values. Consider, for example, the distribution of fatigue lives for a material as shown in Table 6. Assume that these 23 observations were generated from a series of replicate tests, that is, repeated tests under the same simulated service conditions. A substantial range in fatigue lives resulted from these tests, with the greatest fatigue life being more than ten times the lowest observation.

Table 6 Representative fatigue data showing variability in cycles to failure

Life interval, 10^6 cycles	Number of failures	Cycles to failure, 10^6 cycles
0.0-0.5	1	0.425
0.5-1.0	5	0.583, 0.645, 0.77, 0.815, 0.94
1.0-1.5	7	1.01, 1.09, 1.11, 1.21, 1.30, 1.41, 1.49
1.5-2.0	4	1.61, 1.70, 1.85, 1.97
2.0-2.5	2	2.19, 2.32
2.5-3.0	2	2.65, 2.99

3.0-3.5	1	3.42
3.5-4.0	0	. . .
4.0-4.5	0	. . .
4.5-5.0	1	4.66
Total observations	**23**	

The resulting approximate density function for these data is shown in Fig. 7. This figure shows the number of fatigue life observations within uniform cycles-to-failure intervals. Each interval of the histogram shows the frequency of occurrence of fatigue failures within the interval. It is evident that the probability of occurrence of a fatigue failure for this material and test condition is not constant over the range of possible fatigue lives. If 300 observations were available, instead of 23, the shape of the histogram would tend to stabilize. As the number of observations increase, "bumps" in the frequency diagram (as in Fig. 7) caused by random variations in fatigue life would tend to disappear, and the shape will begin to resemble that of a continuous function. A mathematical representation of such a distribution is called a density function.

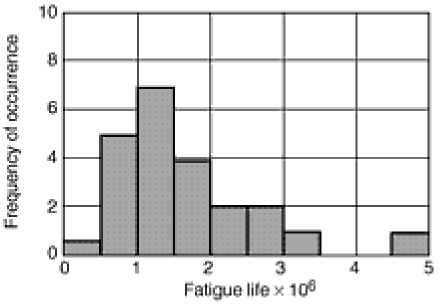

Fig. 7 Histogram of fatigue data from Table 6 showing approximate density function

Cumulative Distribution Functions. Plots of experimental data as density functions, as shown in Fig. 7, provide some useful statistical information. Inferences can be made regarding the central tendencies of the data and the overall variability in the data. However, additional information can be obtained from a data sample like the sample summarized in Table 6, by representing the data cumulatively, as in Table 7, and plotting these data on probability paper, as shown in Fig. 8(a). This is done by ranking the observations from lowest to highest and assigning a probability of failure to each ranked value. These so-called median ranks can be obtained from tables of these values from a statistical test (see, for example, Ref 21).

Table 7 Cumulative distribution of fatigue failures from Table 6

	Cycle interval × 10^6									
	0.0-0.5	**0.5-1.0**	**1.0-1.5**	**1.5-2.0**	**2.0-2.5**	**2.5-3.0**	**3.0-3.5**	**3.5-4.0**	**4.0-4.5**	**4.5-5.0**
No. of failures	1	5	7	4	2	2	1	0	0	1

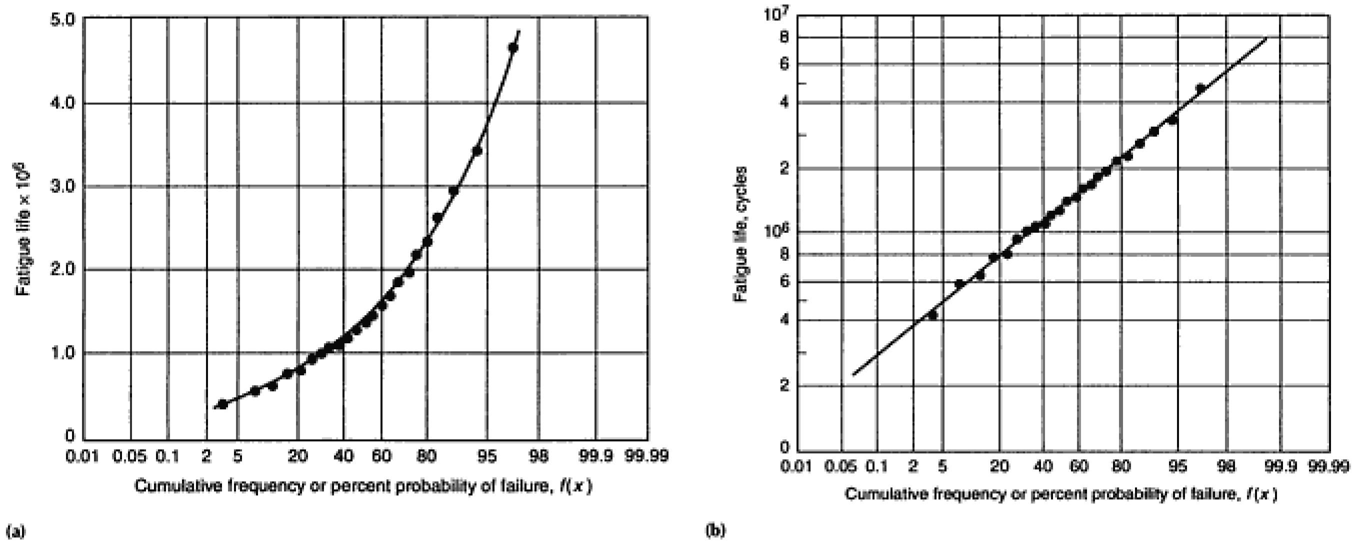

Fig. 8 Cumulative distribution function for fatigue data from Table 6 based on (a) assumed normal distribution and (b) assumed log-normal distribution

Sample versus Population Parameters. When performing a deterministic analysis, the input parameters are defined to represent the material in some specific way. For example, the input parameter may be the average or typical yield strength of a material or a specification minimum value. The implicit assumption is that, given an infinite number of observations of the strength of this material, the assumed average or minimum values would match the "real" values for this infinite population. Of course, the best that can be done is to generate a finite number of observations to characterize the performance of this material (in this case, yield strength); these observations are considered a statistical sample of this never-attainable, infinite population. Intuitively, an increase in the number of observations (the sample size), should increase the accuracy of the sample estimate of the real, or population material properties.

Variability versus Uncertainty. Variability and uncertainty are terms sometimes used interchangeably. However, it is useful when talking about statistical aspects of design to draw a distinction between them. Uncertainty is defined in most dictionaries as "the condition of being in doubt" or something similar to this. In the context of this discussion, uncertainty can be considered the bounds within which the "true" engineering result, such as the average fatigue life of a component, can be expected to fall. To establish this uncertainty in quantitative terms, it is necessary to identify and quantify all factors that contribute to that uncertainty. Generally speaking, the uncertainty in an engineering result is broad in the early stages of a design, and this uncertainty decreases significantly as more experimentation and analysis work is done. This uncertainty is commonly described in terms of confidence limits, tolerance limits, or prediction limits.

Variability is an important element of an uncertainty calculation. The meaning of the term can be drawn directly from its root word, variable. Virtually all elements of a design process can be described as random variables, with some measure of central tendency or average performance and some measure of scatter or variability. For continuous variables, this variability is generally quantified in terms of a sample standard deviation, or sample variance, which is simply the standard deviation squared, σ^2, where σ equals the population standard deviation.

Another commonly used measure of variability is the coefficient of variation, which is defined as the sample mean divided by the sample standard deviation and generally is expressed as a percentage. This normalized parameter allows direct comparisons of relative variability of materials or products that display significantly different mean properties. For example, two different aluminum alloys might have tensile strengths that are described statistically as follows:

Aluminum alloy	**Average tensile strength, ksi**	**Standard deviation, ksi**
No. 1	70	2.5
No. 2	75	4.0

Alloy No. 1 displays a coefficient of variation (COV) of approximately 3.6%, while alloy No. 2 displays a COV of approximately 5.3%. The higher variability of alloy No. 2, as represented by a COV nearly 50% higher than alloy No. 1, could lead to a higher level of uncertainty in the performance of a structure made from the second alloy in comparison to the first alloy.

Precision versus Bias. Precision and bias are statistical terms that are important when considering the suitability of an engineering test method or making a comparison of the relative merits between two or more procedures or processes (Ref 33). A statement concerning the precision of a test method provides a measure of the variability that can be expected between test results when the method is followed appropriately by a competent laboratory. Precision can be defined as the reciprocal of the sample standard deviation, which means that a decrease in the scatter of a test method as represented by a smaller standard deviation of the test results leads directly to an increase in the precision. Conversely, the greater the variability or scatter of the test results, the lower the precision.

The test results of two different processes (e.g.; heat treatments and their effect on tensile strength) can also be statistically compared, and a statement made regarding the precision of one process compared to another. Such a statement of relative precision is only valid if no other potentially significant variables, such as different test machines, laboratories, or machining practices are involved in the comparison.

The bias of a set of measurements quantifies the difference in those test results from an accepted reference value or standard. The concept of a bias can also be used to describe the consistent difference between two operators, test machines, testing periods, or laboratories. The term accuracy is sometimes used as a synonym for bias, but it is possible to identify a bias between two sets of measurements or procedures without necessarily having any awareness of which set is most accurate. In order to make quantitative statements about absolute bias or accuracy, it is necessary to have a known baseline or reference point; such fixed points are seldom available in the real world of an engineer.

Independent versus Dependent Variables. Many engineering analyses involve the prediction of some outcome based on a set of predefined input conditions. A very simple example is the prediction of stress in the elastic range for a metal, based on a measured strain and an estimated or measured value for elastic modulus. Another more complex example is the prediction of the fatigue resistance of a part based on estimated local stress or strain amplitudes and experimentally determined fatigue parameters. In general, relationships such as these are developed through a regression analysis, in which the predicted outcome, y, is estimated from a series of terms written as a function of one or more input quantities, x_i, and regression parameters, A_i, as follows:

$$y = A_0 + A_1 f_1(x) + A_2 f_2(x) \ldots \quad \textbf{(Eq 2)}$$

In this expression, the predicted result, *y,* is the dependent variable, while the defined quantity, *x,* is the independent variable. In some cases, multiple independent variables are needed in combination to realistically estimate the independent variable(s).

Why Not Just Assume Normality and Forget the Complications? The first assumption that most engineers will make when applying statistics to an engineering problem is that the property in question is normally distributed. The normal distribution is relatively simple mathematically, is well understood, and is well characterized. The engineering statistics applications where nonnormal statistical distributions and nonparametric (distribution-free) approaches are used probably do not total the number of applications based on normal statistics.

The assumption of normality is reasonable in many cases where only mean trends or average properties are of interest. The importance of verifying this assumption increases when properties removed from the mean or average are being addressed, such as an estimated first percentile value of a design factor or a value 2 or 3 standard deviations below the mean. The assumptions that are made regarding underlying statistical distributions can have a significant impact on the meaningfulness of the answers that result.

Statistical Distributions

Statistical distributions model various physical, mechanical, electrical, and chemical properties, as well as the number of occurrences of events. There are seven well-known and widely used statistical distributions: normal, log normal, Weibull, and exponential, which are continuous in nature and binomial Poisson and hypergeometric, which are discrete functions. Each of these statistical distributions are briefly described below. References 34, 35, and 36 provide a comprehensive collection of information about numerous statistical distributions used in the development of statistical theory and practice. Reference 21 is a useful layman's source on statistical distributions and their practical application.

The normal distribution is the most widely used and best understood statistical distribution. In addition to its widespread use as an approximation to the distributions of many computed statistics, the normal distribution is frequently used to model various physical, mechanical, electrical, and chemical properties--for example, tensile strength, hardness, conductivity, and elastic modulus. Many properties that scatter randomly about a well-defined mean value, without either positive or negative bias, also tend to follow a normal distribution.

The primary limitation associated with the modeling of physical measurements with the normal distribution is its symmetry of average value. Thus, skewed or asymmetric populations are not modeled well by the normal distribution. The main advantage of the normal distribution is the large body of literature available describing procedures for the analysis of normally distributed data.

Figure 9 illustrates a histogram that describes the distribution of tensile yield strengths for a particular material. The number of observations in each interval is recorded. Continuous probability density functions are superimposed over the histogram to indicate the conformity of these data to a normal distribution as compared with either a two-parameter or a three-parameter Weibull distribution.

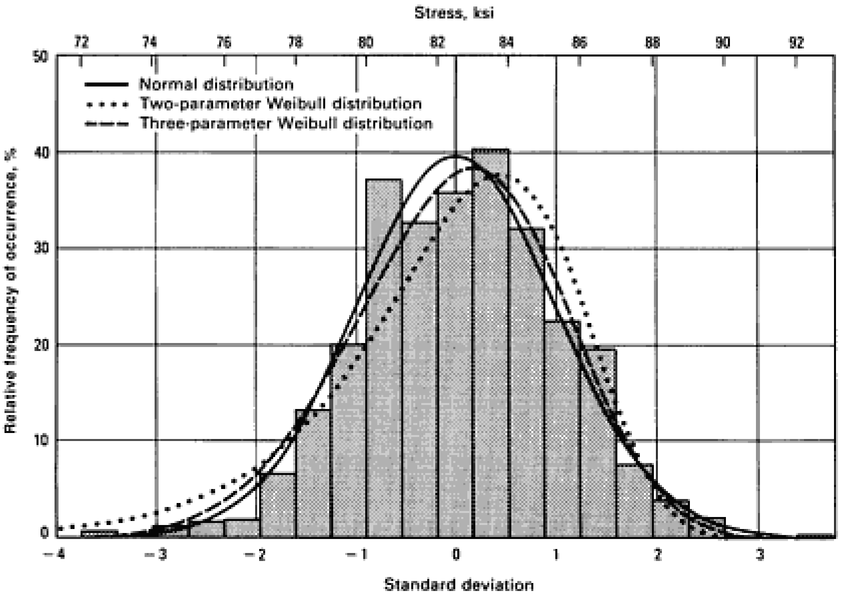

Fig. 9 Histogram of tensile yield strength values with superimposed probability density functions

Log-Normal Distribution. Probably the second most often assumed distribution for engineering random variables is the log-normal distribution. Of course, the log-normal distribution is really just a special case of the normal distribution, where the quantities that are assumed to be normally distributed are the logarithms of the original observations. For example, when the logarithms of the fatigue lives of the material listed in Table 6 were completed and the computed values were ranked and plotted on normal probability paper, a nearly straight line resulted (Fig. 8b). The data trends deviate from linearity only at the very low- and high-fatigue lives.

Weibull distribution is used frequently in representing engineering random variables because it is very flexible. It was originally proposed (Ref 37) to represent fatigue data, but it is now used to represent many other types of engineering data. For the modeling of fatigue strength at a given life, it has been argued that only the Weibull distribution is appropriate (Ref 38). One of the reasons that the Weibull distribution is popular is that data can be plotted on Weibull paper and the conformance of these data to the Weibull distribution can be evaluated by the linearity of the cumulative distribution function in the same way as normal distribution (Fig. 9).

Exponential distribution, which is a special case of the Weibull distribution, has been found to be useful in the analysis of failure rates of complete systems or assemblies, such as light bulbs, water heaters, and automobile transmissions, or where their failures result from chance occurrence alone, such as a wheel hitting a large pothole.

Binomial distribution may be applicable where the random variable is discrete and takes on non-negative integer values. It is used commonly in developing sampling plans for periodic inspections of manufacturing or material quality. For example, it is used to model the number of defective items in samples drawn from large lots of items (such as electrical parts) submitted to inspection.

Other Discrete Distributions. Two other common variations of the binomial distribution are the hypergeometric and the Poisson distributions. The hypergeometric distribution is used for the same kinds of applications as the binomial distribution, except that for the binomial, the percentage of defective items is assumed to be constant throughout the experiment.

The Poisson distribution differs from the binomial and hypergeometric distributions in that the number of times that an event occurs is not known, but the probability of occurrence of the event is known.

Statistical Procedures

Many different statistical techniques can be useful in analysis of mechanical-property data. This section presents brief descriptions of procedures that are used frequently (Ref 39). More detailed descriptions of these and other statistical techniques and tables in their various forms can be found in a number of workbooks and texts (for example, Ref 40).

Goodness-of-fit tests can be used to establish whether a sample can realistically be assumed to follow a normal distribution. The Anderson-Darling goodness-of-fit test for normality can be used to determine whether the density function that fits a given set of data can be approximated by a normal curve. The test involves a numerical comparison of the cumulative distribution function for observed data with that for the fitted normal curve over the entire range of the property being measured. Arithmetic normal probability paper is recommended for graphic illustration of the degree to which a normal distribution fits a set of data. Logarithmic normal probability paper can be used to determine whether the distribution of data could be normalized by a logarithmic transformation. One axis is scaled in units of the property measured, and the other axis is a nonlinear scale of probability. For further information on goodness-of-fit tests, refer to Ref 41 and 42.

Tests of significance, which include the F test and t test, are used in determining whether the populations from which two samples are drawn are identical. The F test is used to determine whether two products differ with regard to their variability. The t test is used to determine whether two products differ with regard to their average properties. If they do, it can be concluded that the two products do not belong to the same population.

In making the t test, it is assumed that the variances of two products are nearly equal, as first determined from the F test. If the F test shows that the variances are significantly different, there is no need to conduct the t test.

Data Regression Techniques. When it is suspected that the average of one measured value varies linearly or curvilinearly with some other measured value, a regression analysis is often used to investigate and describe the relationship between the two quantities. Examples are effect of product thickness on tensile strength, effect of temperature on yield strength, and effect of stress on cycles to failure or time to rupture. Reference 43 describes mathematical techniques for performing linear regression computations.

Related ASTM Engineering Statistics Standards

Table 8 lists standards published by the American Society for Testing and Materials (ASTM) that address statistical issues relevant to engineering design. These standards are maintained by ASTM Committee E11 on Statistical Methods. A primary purpose of this group is to advise other ASTM committees in the area of statistics, and to provide information for general application.

Table 8 ASTM standards related to engineering statistics

ASTM No.	Title
Statistics terminology	
D 4392	"Terminology for Statistically Related Terms"
E 177	"Practice for Use of the Terms Precision and Bias in ASTM Test Methods"
E 456	"Terminology Related to Statistics"
E 1325	"Terminology Relating to Design of Experiments"
E 1402	"Terminology Relating to Sampling"

Statistical conformance with specifications	
D 3244	"Practice for Utilization of Test Data to Determine Conformance with Specifications"
E 122	"Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process"
Statistical control and comparison of test methods	
D 4356	"Practice for Establishing Consistent Test Method Tolerances"
D 4853	"Guide for Reducing Test Variability"
D 4855	"Practice for Comparing Test Methods"
E 1323	"Guide for Evaluating Laboratory Measurement Practices and the Statistical Analysis of the Resulting Data"
Statistical analysis of test data	
E 178	"Practice for Dealing with Outlying Observations"
E 739	"Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ε-N) Fatigue Data"
Statistical guidelines for interlaboratory testing programs	
D 4467	"Practice for Interlaboratory Testing of a Test Method that Produces Non-Normally Distributed Data"
E 691	"Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method"
Statistical issues in development of sampling plans	
D 4854	"Guide for Estimating the Magnitude of Variability from Expected Sources in Sampling Plans"
E 105	"Practice for Probability Sampling of Materials"
E 141	"Practice for Acceptance of Evidence Based on the Results of Probability Sampling"

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Total Life Cycle in Design

It is an accepted principle of engineering to design a product for minimum cost, consistent with fulfilling the functional requirements of the product. It is tempting to define the cost of a product strictly on the basis of component and labor costs (plus allowances for overhead, selling cost, and profit). However, such accounting neglects several important items in the total cost of the product to the user, such as cost of energy to operate the product, cost of maintaining the product, depreciation, and cost of disposal. In addition to the cost of a product to its producer and user, there is the cost to society at large; some of the components of this cost are consumption of raw materials and energy and the impact of the product on the environment. The relative importance of considering the cost to the user and to society during design depends in part on the nature of the product. An automobile, for instance, has considerable user and societal costs; for a bolt, these costs are smaller, harder to identify, and easier to neglect.

To a materials engineer, the concept of total life cycle must include the total life of the product, as discussed above and in Table 2, but should also include the total life cycle of the components and materials in the product. Whenever possible, a product should be designed so that components that do not wear out can be reused, or so that the materials in the product can be recycled.

Life-cycle analysis (LCA) refers to the "cradle to grave" assessment of the energy requirements and environmental impacts of a given product design. All aspects of the total life cycle of the product are considered, including raw-material extraction from the earth and product manufacture, use, recycling (including design for recycling), and disposal. Key factors considered in the life-cycle engineering approach are examined in the Section on "Recycling and Life-Cycle Analysis" in this Handbook.

Energy Requirements. Reuse of components and materials obviously conserves raw materials, such as the ore from which a metal is made, but it also conserves the energy required to extract the metal from the ore. Basic metal-production operations are highly energy intensive. It has been estimated that 95% of the energy required to manufacture aluminum beverage cans from ore can be saved if metal in the cans is recycled. It may be possible to conserve energy by choosing materials that do not require heat treatment but still have adequate strength. Heavily drafted cold-drawn and stress-relieved steel bars can have yield strengths of 690 MPa (100 ksi); for many purposes, such bars can be used in place of hardened-and-tempered bars. The potential for conservation of scarce resources, particularly those that might be subject to manipulation for economic or political gain, is apparent in these two examples.

As suggested above, the energy required to operate a mechanical device can represent a significant portion of its total life-cycle cost. For example, the cost of electricity used to operate an air conditioner for the duration of the warranty period may be greater than its purchase price.

Producibility. The question of producibility affects engineering design at several levels. The most basic question is whether the technology required to economically produce the desired quantity of the item exists. A product should be designed in accordance with established technological practice whenever possible; working at the limit of technology leads to higher scrap levels and difficulties in production, and advancing the limit of technology requires a developmental program before production can begin. A second question concerns the capability of the factory (or entire industry) to produce the desired number of parts. The third question concerns utilization of existing equipment and personnel. Some of the answers to these questions are managerial prerogatives, but it is usually desirable for designers to analyze the various possibilities and present a set of alternatives, together with possible consequences, advantages, and disadvantages of each, to management.

Durability, or intended service lifetime, is one of the parameters on which a design must be based. In general, basic goals for service lifetime are established for, rather than by, designers. As in the case of producibility, it may be desirable for a designer to develop alternative combinations of material and design that could significantly affect the anticipated service life of the product.

Quality assurance should be an integral part of the manufacturing process of any product, especially because the possible consequences of permitting deficient products to reach the marketplace can be dire. This article does not attempt to describe a quality assurance program, or how to develop such a program; rather, it emphasizes the importance of such a program and points out how design and quality assurance are interrelated.

A designer must know the types and severity of discontinuities that can be detected in a quality assurance program and have an appropriate level of confidence in the detection methods. By knowing what can be expected from the quality assurance program, the designer can then provide a margin of safety to compensate for the existence of discontinuities that cannot be detected. This is part of the basic philosophy of fracture mechanics. A similar approach is applicable to design of redundant systems in the product. In either case, the product should be designed with the capabilities and limitations of the quality assurance program in mind.

Handling requirements of various products are too frequently neglected in engineering design. Almost without exception, a product is made in one location and used in another. Thus, it is essential to provide means for transporting it from the manufacturer to the seller to the user; the means of transportation can affect the design of the product in several ways. The most obvious concern is to ensure that the product will not be degraded in handling, transit, or storage. Whenever feasible, a product should be designed against the possibility of damage caused by normal handling. A product that can be easily damaged in handling must be carefully (and expensively) protected by packaging or special shipping procedures. It is also important to design a product to minimize shipping and storage space requirements. For example, wastebaskets are usually designed to be nested during handling; many wastebaskets have lugs or other design features that limit nesting in order to permit easy separation. Particularly for consumer products, the design of packages may not be considered a part of product design, but it is still appropriate for a product designer to consider packaging requirements that might result from various design alternatives.

Other Major Factors in Design

Besides the functional factors listed in Table 1 and the total life-cycle considerations described in Table 2, several other major factors affect design and materials selection; some of them are listed in Table 3.

State of the Art

Most of the time, the state of the art in a particular field can be inferred from an engineering evaluation of products currently on the market. Existing products may lack capabilities that could be provided by a new product. The extent of improvement might range from purely cosmetic (which might be the case for a new product intended to capitalize on the market acceptance of an established product) to complete redesign resulting in an entirely new product unlike anything previously produced. The state of the art can be defined not only by existing products but also by industrial and societal standards, technical publications, and patents. Patent infringement is often considered a matter for legal departments, but technical personnel are often able to analyze technological aspects of patents on devices and processes that might be applicable to new products.

Designing to Codes and Standards

Many products are subject to either mandatory or voluntary standards. By definition, a "code" is any set of standards set forth and enforced by a local government for the protection of public safety, health, etc., as in the structural safety of buildings (building code), health requirements for plumbing, ventilation, etc. (sanitary or health code), and the specifications for fire escapes or exits (fire code)." "Standard" is defined as "something considered by an authority or by general consent as a basis of comparison; an approved model."

As a practical matter, codes tell the user *what* to do and *when* and under what circumstances to do it. Codes are often legal requirements that are adopted by local jurisdictions that then enforce their provisions. Standards tell the user *how* to do it and are usually regarded only as recommendations that do not have the force of law. As noted in the definition for code, standards are frequently collected as reference information when codes are being prepared. It is common for sections of a local code to refer to nationally recognized standards. In many instances, entire sections of the standards are adopted into the code by reference, and then become legally enforceable. A list of such standards is usually given in an appendix to the code.

The Need for Codes and Standards. The information contained in codes and standards is of major importance to designers in all disciplines. As soon as a design problem has been defined, a key component in the formulation of a solution to the problem should be the collection of available reference materials; codes and standards are an indispensable part of that effort. Use of codes and standards can provide guidance to the designer about what constitutes good practice in that field and ensures that the product conforms to applicable legal requirements.

The fundamental need for codes and standards in design is based on two concepts: part/component interchangeability and compatibility. Standardization of parts within a particular manufacturing company to ensure interchangeability is only one part of the industrial production problem. The other part is compatibility. What happens when parts from one company, working to their standards, have to be combined with parts from another company, working to their standards? Will parts from company A fit with parts from company B? Yes, but only if the parts are compatible. In other words, the standards of the two companies must be the same.

Common Examples of Codes and Standards. Most materials engineers are familiar with the many professional society codes that have been developed. The American Society of Mechanical Engineers (ASME) publishes the Boiler and Pressure Vessel Code, which has been used as a design standard for many decades. The Society of Automotive Engineers (SAE) publishes hundreds of standards relating to the design and safety requirements for vehicles and their appurtenances. ASTM publishes thousands of standards relating to materials and the methods of testing. These standards are published in a set of 70 volumes divided into 15 separate sections. The standards are developed on a consensus basis with several steps in the review process. Initial publication of a standard is on a tentative basis; such standards are marked with a T until finally accepted. Periodic reviews keep the requirements and methods current. Because designers frequently call out ASTM testing requirements in their materials specifications, the designer should routinely check ASTM listings to make certain the applicable version is being called for.

Coordination, approval, and distribution of many domestic standards fall under the auspices of the American National Standards Institute (ANSI), New York, NY. A sponsoring trade association will request that ANSI review its standard. A review group is then formed that includes members of many groups other than the industry. This expands the area of consensus and is an essential feature of the ANSI process. Table 9 gives a partial list of the many organizations that act as sponsors for the standards that ANSI prepares under their consensus format.

Table 9 Sponsoring organizations for standards published by the American National Standards Institute

Acronym	Organization
AAMA	American Apparel Manufacturers Association 2500 Wilson Blvd., Arlington, VA 22201 (703) 524-1864
AAMA	American Architectural Manufacturers Association 1540 E. Dundee Rd., Palatine, IL 60067 (708) 202-1350
AAMI	Association for the Advancement of Medical Instrumentation 3330 Washington Blvd., Arlington, VA 22201 (703) 525-4890
AASHTO	American Association of State Highway and Transportation Officials 444 N. Capitol St., N.W., Washington, D.C. 20001 (202) 624-5800
AATCC	American Association of Textile Chemists and Colorists P.O. Box 12215, Research Triangle Park, NC 22709-2215 (919) 549-8141
ABMA	American Bearing Manufacturers Association and Anti-Friction Bearing Manufacturers Association (AFBMA) 1900 Arch St., Philadelphia, PA 19103 (215) 564-3484
. . .	American Boat and Yacht Council 3069 Solomon's Island Rd., Edgewater, MD 21037-1416 (410) 956-1050
ACI	American Concrete Institute P.O. Box 19150, Detroit, MI 48219 (313) 532-2600
ADA	American Dental Association 211 E. Chicago Ave., Chicago, IL 60611 (312) 440-2500
AGA	American Gas Association 1515 Wilson Blvd., Arlington, VA 22209 (703) 841-8400
AGMA	American Gear Manufacturers Association 1500 King St., Alexandria, VA 22314 (703) 684-0211
AHAM	Association of Home Appliance Manufacturers 20 W. Wacker Dr., Chicago, IL 60606

	(312) 984-5800
AIA	Automated Imaging Association 900 Victor's Way, Ann Arbor, MI 48106 (313) 994-6088
AIAA	American Institute of Aeronautics and Astronautics 370 L'Enfant Promenade, S.W., Washington, D.C. 20024 (202) 646-7400
AIIM	Association for Information and Image Management 1100 Wayne Ave., Silver Spring, MD 20910 (301) 587-8202
AISC	American Institute of Steel Construction, Inc 1 E. Wacker Dr., Chicago, IL 60601-2001 (312) 670-2400
ANS	American Nuclear Society 555 N. Kensington Ave., La Grange Park, IL 60525 (708) 352-6611
API	American Petroleum Institute 1220 L St., N.W., Washington, D.C. 20005 (202) 682-8000
ARI	Air-Conditioning and Refrigeration Institute 4301 N. Fairfax Dr., Arlington, VA 22203 (703) 524-8800
ASAE	American Society of Agricultural Engineers 2950 Niles Rd., St. Joseph, MI 49085-9659 (616) 429-0300
ASCE	American Society of Civil Engineers 1015 15th St., N.W., Washington, D.C. 20005 (202) 789-2200
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers 1791 Tullie Circle, N.E., Atlanta, GA 30329 (404) 636-8400
ASME	American Society of Mechanical Engineers 345 E. 47th St., New York, NY 10017 (212) 705-7722
ASQC	American Society for Quality Control 611 E. Wisconsin Ave., Milwaukee, WI 53201

	(414) 272-8575
ASSE	American Society of Sanitary Engineering P.O. Box 40362, Bay Village, OH 44140 (216) 835-3040
AWS	American Welding Society 550 LeJeune Rd., N.W., Miami, FL 33126 (305) 443-9353
AWWA	American Water Works Association 6666 W. Quincy Ave., Denver, CO 80235 (303) 794-7711
BHMA	Builders Hardware Manufacturers Association 355 Lexington Ave., New York, NY 10017 (212) 661-4261
CEMA	Conveyor Equipment Manufacturers Association 9384-D Forestwood Ln., Manassas, VA 22110 (703) 330-7079
CGA	Compressed Gas Association 1725 Jefferson Davis Highway, Arlington, VA 22202-4100 (703) 412-0900
CRSI	Concrete Reinforcing Steel Institute 933 Plum Grove Rd., Schaumburg, IL 60173 (708) 517-1200
DHI	Door and Hardware Institute 14170 Newbrook Dr., Chantilly, VA 22021-2223 (703) 222-2010
EIA	Electronic Industries Association 2500 Wilson Blvd., Arlington, VA 22201 (703) 907-7550
FCI	Fluid Controls Institute P.O. Box 9036, Morristown, NJ 07960 (201) 829-0990
HI	Hydraulic Institute 9 Sylvan Way, Parsippany, NJ 07054-3802 (201) 267-9700
HTI	Hand Tools Institute 25 North Broadway, Tarrytown, NY 10591 (914) 332-0040

ICEA	Insulated Cable Engineers Association P.O. Box 440, South Yarmouth, MA 02664 (508) 394-4424
IEC	International Electrotechnical Commission Geneva, Switzerland. Communications: c/o ANSI 11 W. 42nd St., New York, NY 10036 (212) 642-4900
IEEE	Institute of Electrical and Electronics Engineers 345 E. 47th St., New York, NY 10017 (212) 705-7900
IESNA	Illuminating Engineering Society of North America 120 Wall St., New York, NY 10005-4001 (212) 248-5000
IPC	Institute for Interconnecting and Packaging Electronic Circuits 2215 Sanders Rd., Northbrook, IL 60062-6135 (708) 509-9700
ISA	Instrument Society of America P.O. Box 12277 Research Triangle Park, NC 27709 (919) 549-8411
ISDI	Insulated Steel Door Institute 30200 Detroit Rd., Cleveland, OH 44145-1967 (216) 899-0010
ISO	International Organization for Standardization Geneva, Switzerland. Communications: c/o ANSI, 11 W. 42nd St., New York, NY 10036 (212) 642-4900
NAAMM	National Association of Architectural Metal Manufacturers 11 S. La Salle St., Chicago, IL 60603 (312) 201-0101
NAPM	National Association of Photographic Manufacturers 550 Mamaroneck Ave., Harrison, NY 10528 (914) 698-7603
NEMA	National Electrical Manufacturers Association 1300 N. 17th St., Rosslyn, VA 22209 (703) 841-3200
NFoPA	National Forest Products Association 1111 19th St., N.W., Washington, D.C. 20036 (202) 463-2700

NFiPA	National Fire Protection Association 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101 (617) 770-3000
NFlPA	National Fluid Power Association 3333 N. Mayfair Rd., Milwaukee, WI 53222-3219 (414) 778-3344
NISO	National Information Standards Organization 4733 Bethesda Ave., Bethesda, MD 20814 (301) 654-2512
NSF	National Sanitation Foundation, International 4201 Wilson Blvd., Arlington, VA 22230 (703) 306-1070
NSPI	National Spa and Pool Institute 2111 Eisenhower Ave., Alexandria, VA 22314 (703) 838-0083
OPEI	Outdoor Power Equipment Institute, Inc. 341 S. Patrick St., Alexandria, VA 22314 (703) 549-7600
RESNA	Rehabilitation Engineering and Assistive Technology Society of North America 1700 N. Moore St., Arlington, VA 22209-1903 (703) 524-6686
RIA	Robotic Industries Association 900 Victors Way, Ann Arbor, MI 48106 (313) 994-6088
RMA	Rubber Manufacturers Association 1400 K St., N.W., Washington, D.C. 20005 (202) 682-4800
SAAMI	Sporting Arms and Ammunition Manufacturers Institute Flintlock Ridge Office Center, 11 Mile Hill Rd., Newtown, CT 06470 (203) 426-4358
SAE	Society of Automotive Engineers 400 Commonwealth Dr., Warrendale, PA 15096 (412) 776-4841
SIA	Scaffold Industries Association 14039 Sherman Way, Van Nuys, CA 91405-2599 (818) 782-2012
SMA	Screen Manufacturers Association 2545 S. Ocean Blvd., Palm Beach, FL 33480-5453 (407) 533-0991

SMPTE	Society of Motion Picture and Television Engineers 595 W. Hartsdale Ave., White Plains, NY 10607 (914) 761-1100
SPI	The Society of the Plastics Industry, Inc. 1275 K St., N.W., Washington, D.C. 20005 (202) 371-5200
TIA	Telecommunications Industries Association 2001 Pennsylvania Ave., N.W., Washington, D.C. 20006-4912 (202) 457-4912

ANSI circulates copies of the proposed standard to all interested parties seeking comments. A time frame is setup for receipt of comments, after which a Board of Standards Review considers the comments and makes what it considers necessary changes. After more reviews, the standard is finally issued and published by ANSI, listed in their catalog, and made available to anyone who wishes to purchase a copy. A similar process is used by the International Standards Organization (ISO), which began to prepare an extensive set of worldwide standards in 1996. Standards published by ISO members are also listed in ANSI catalogs.

Standards Information Services. Copies of standards and information about documents published by the more than 350 code- and standard-generating organizations in the United States and several other countries can be obtained from resellers such as Global Engineering Documents, Englewood, CO. They provide information on CD-ROM, magnetic tape, microfilm, or microfiche formats. Similar services exist in many countries throughout the world.

Human Factors and Safety in Design

Human factors in design describe the interactions between a device and anyone who uses or maintains it. Examples of human factors in design include designing the handle of a portable electric drill to fit comfortably into either hand of the user, arranging gages and controls on an automobile dashboard to be easily seen or reached, and designing an ejector to remove the beaters of an electric mixer. Human factors also include operational methods and procedures, testing and evaluating these methods and procedures, job design, development of job aids and training materials, and selection and training of people who will be users.

One branch of industrial engineering that deals specifically with human factors is referred to as "ergonomics"; contact with persons involved in such research would be useful to designers. References 44, 45, and 46 include examples of useful references describing human factors in design.

Safety in Design. The designer/manufacturer of any product (e.g., consumer product, industrial machinery, tool, system, etc.) has a major obligation to make the product safe (i.e., reduce the risks associated with the product to an acceptable level). In this context, "safe" means a product with an irreducible minimum of danger (as defined in the legal sense), that is, safe not only with regard to intended use (or uses) but also all unintended, but foreseeable, uses. For example, consider the common flat-tang screw driver. Its intended use is well known. Can anyone say that they have never used such a screwdriver for any other purpose? It must be designed and manufactured to be safe in all these uses.

There are three aspects, or stages, in designing for safety:

1. Make the product safe (i.e., design all hazards out of the product).
2. If it is impossible to eliminate all hazards in design, provide guards that eliminate the danger.
3. If it is impossible to provide proper and complete guarding, provide appropriate directions and warnings.

Although the principles or specific guidelines for carrying out these stages in designing for safety are beyond the scope of this article, there is an abundance of literature on safe practices in design (see, for example, Ref 47, 48, 49, 50).

Documents pertaining to safety and control or elimination of workplace hazards can also be obtained from ANSI and the National Safety Council.

Aesthetics

Aesthetics is an important aspect of the design of almost any product, but it is an aspect that should not be allowed to compromise functional requirements. Some consumer products are sold almost exclusively by aesthetic appeal; design of such products is usually assigned to artists. However, aesthetic appeal is important even for industrial products. A smooth or shiny finish, an artistically pleasing shape, or an appearance of ruggedness and durability may have little or no influence on the ability of the product to perform its function but may, nevertheless, have a considerable effect on the attitude of a potential buyer or on worker acceptance when the item is put into service.

Cost

Assuming that a product meets the basic functional requirements established for it, the most important single factor in its design and manufacture is cost. The cost of any product must be competitive with the cost of comparable products already on the market. Whether there is a directly comparable product or not, the cost must be low enough to convince a prospective purchaser that the benefits to be derived from the product exceed its cost. Cost-benefit studies almost always precede the purchase of major pieces of manufacturing equipment.

Cost generally enters the design process as one of several criteria against which the merit of a design is judged. Whenever a choice exists between different materials, designs, or manufacturing processes, the least costly alternative will be chosen, provided that the basic functional requirements for the product can still be met. In some instances, the possibility of significant cost reduction will justify re-evaluation of basic functional requirements and performance specifications; it may be possible to modify the design goals slightly and thereby significantly reduce costs. However, it is important to remember that any modification of functional requirements and performance specifications can adversely affect utility and marketability.

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Factors in Materials Selection

Introduction

THE SELECTION OF ENGINEERED MATERIALS is an integral process that requires an understanding of the interaction between such factors as materials properties, manufacturing and fabrication characteristics, and the design considerations described in the previous article. Two often cited reasons for selecting a certain material for a particular application are (a) the material has always been used in that application and (b) the material has the right properties. Neither reason is evidence of original thinking or even careful analysis of the application. The collective experience gained from common usage of a material in a particular application is useful information, but not justification in itself for selecting a material. The time has passed when each application has its preferred material and a particular material its secure market. In the context in which it is frequently mentioned, the term "property" connotes something that a material inherently possesses. On the contrary, a property should be regarded as the response of the material to a given set of imposed conditions. It must also be recognized that this property should be that of the material in its final available and processed form. Tabulated properties data, such as those available from handbooks, standards organizations, computerized databases, and other sources of materials information summarized in Ref 1 are helpful, but such information must be used judiciously and must be relevant to a particular application.

Regardless of specific expertise, every engineer concerned with hardware of any description (and this includes essentially all engineers) must deal constantly with selecting an appropriate material (or combination of materials) for the design. Except in trivial applications, it certainly is not sufficient to indicate that the components should be "steel" or "aluminum" or "plastic". Rather, the engineer must focus attention, knowledge, and skill on the general factors in materials selection listed in Table 1. It is obvious that these are inseparable and interwoven with the factors described in Tables 1 to 3 in the article "Design Factors" in this Section.

Table 1 General factors in materials selection

- Functional requirements and constraints
- Material properties (see Table 2)
- Manufacturing process considerations
- Fabricability (see Table 2)
- Design configuration
- Available and alternative materials
- Corrosion and degradation in service
- Thermal stability
- Properties of unique interest

    - High density
    - High stiffness-to-weight ratio
    - Low melting point
    - Special thermal expansion properties
    - Electrical conductivity/superconductivity
    - Wear resistance
    - Biocompatibility

- Cost

In principle, a mathematical expression describing the merit of an engineering design as a function of all these variables, differentiating it with respect to each of the criteria for evaluation, and solving the resulting differential equations to obtain the ideal solution could be written. This is not a reality, however, the principle is valid and should provide a basis for action by the designer. In some instances, a standard, readily available component can be much less costly than, and yet nearly as effective as, a component of optimized, nonstandard design.

Reference

1. J.H. Westbrook, Sources of Materials Property Data and Information, *Materials Selection and Design,* Vol 20, *ASM Handbook,* ASM International, 1997, p 491-506

Materials Properties

The performance or functional characteristics of a material are expressed chiefly by physical, mechanical, thermal, electrical, magnetic, and optical properties. Material properties are the link between the basic structure and composition of the material and the service performance of the part (Fig. 1).

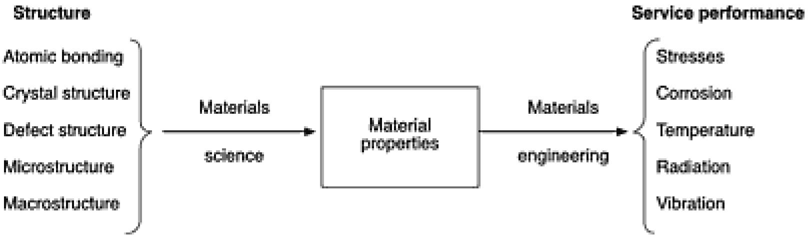

Fig. 1 The role played by material properties in the selection of materials

An important role of the materials engineer is to assist the designer in making meaningful connections between materials properties and the performance of the part or system being designed. For most mechanical systems, performance is limited, not by a single property, but by a combination of them.

Mechanical Properties

One question usually asked in selecting materials is whether strength is adequate to withstand the stresses imposed by service loading. Although the primary selection criterion is often strength, it also may be toughness, corrosion resistance, electrical conductivity, magnetic characteristics, thermal conductivity, specific gravity, strength-to-weight ratio, or some other property listed in Table 2. For example, in residential water service, where the water pressure is relatively low, weaker and more expensive copper tubing might be a better choice than stronger steel pipe. Steel pipe comes in sections and is joined by threaded connections with elbows at corners, whereas soft copper can be obtained in coils and can be easily bent around corners. Thus, the lower installation cost of copper can overcome the higher material cost. Also, because of the relatively low water pressure, the strength of copper would be adequate, and the greater strength of steel unnecessary. Furthermore, in the event of freezing, copper usually yields instead of bursting; in many regions of the country, it is more resistant to corrosion by the local water than steel. In general, the usual criterion for selection is not just one property, such as strength, but some combination of properties, manufacturing characteristics, and cost.

Table 2 Materials properties that must be considered during the materials selection process

Physical properties
Crystal structure Atomic weight Density Melting point Boiling point Vapor pressure Viscosity Porosity Permeability Reflectivity Transparency Optical properties Dimensional stability
Electrical properties

- Conductivity
- Resistivity
- Dielectric constant
- Hall coefficient (effect)
- Superconducting temperature

Magnetic properties

- Magnetic susceptibility
- Magnetic permeability
- Coercive force
- Saturation magnetization
- Transformation (Curie) temperature
- Magnetostriction

Nuclear properties

- Half-life
- Cross section
- Stability

Mechanical properties

- Hardness
- Modulus of elasticity
  - Tension
  - Compression
- Poisson's ratio
- Stress-strain curve
- Yield strength
  - Tension
  - Compression
  - Shear
- Ultimate strength
  - Tension
  - Shear
  - Bearing
- Fatigue properties
  - Smooth
  - Notched
  - Corrosion fatigue
  - Rolling contact
  - Fretting
- Charpy transition temperature
- Fracture toughness (K_{Ic})
- High-temperature behavior

- Creep
- Stress rupture

Damping properties

Wear properties

- Galling
- Abrasion
- Erosion

Cavitation

Spalling

Ballistic impact

Thermal properties

Conductivity

Specific heat

Coefficient of thermal expansion

Latent heat of fusion

Emissivity

Absorptivity

Ablation rate

Fire resistance

Chemical properties

Position in electromotive series

- Galvanic corrosion

Corrosion and degradation

- Atmospheric
- Fresh water
- Salt water
- Acids
- Hot gases
- Ultraviolet

Oxidation

Thermal stability

Biological stability

Stress corrosion

Hydrogen embrittlement

Hydraulic permeability

Fabrication properties

Castability

Heat treatability

Hardenability

Formability

Machinability

Weldability

Ultimate tensile strength is a commonly measured and widely reported indication of the ability of a material to withstand loads. However, the direct application of tensile-strength data to design problems is extremely difficult. First of all, the definition of "ultimate tensile strength" is the maximum stress (based on initial cross-sectional area) that a specimen can withstand before failure; it occurs at the onset of plastic instability. Thus, any component loaded to its ultimate tensile strength is likely to fracture immediately. Secondly, if the design is based on a fraction of the ultimate strength, there is the question of what fraction provides adequate strength and safety, together with efficient use of the material. Finally, there seems to be only a rough correlation between tensile strength and material properties such as hardness and fatigue strength at a specified number of cycles, and no correlation whatsoever between tensile strength and properties such as resistance to crack propagation, impact resistance. or proportional limit.

Yield strength indicates the lowest measurable stress at which permanent deformation occurs. This information is necessary to estimate the forces required for forming operations. Yield strength is also useful in considering the effects of a single-application overload; most structures must be designed so that a foreseeable overload will not exceed the yield strength.

Hardness is another widely measured material property and is useful for estimating the wear resistance of materials and estimating approximate strength of steels. Its most widespread application is for quality assurance in heat treating. However, only rough correlation can be made between hardness and other mechanical properties or between hardness and behavior of materials in service.

Ductility of a metal, usually measured as the percent reduction in area or elongation that occurs during a tensile test, is often considered an important factor in material selection. It is assumed that, if a metal has a certain minimum elongation in tensile testing, it will not fail in service through brittle fracture. It is also assumed that if a little ductility is good, a lot is better. Neither of these assumptions is accurate. Metals normally considered very ductile can fail in a seemingly brittle manner, such as under fatigue or stress-corrosion conditions, or when the service temperature is below the ductile-to-brittle transition temperature. How much ductility is actually usable under service conditions and how best to measure it are very controversial. Several estimates of usable ductility (such as the ability of materials to absorb the movement within a large structure that is necessary to equalize the load among all of the members of the structure) fall in the range of 1 to 2% elongation in tensile testing. Larger amounts of ductility only indicate the possibility of more extensive permanent deformation of the structure. In many structures, any permanent deformation destroys the usefulness of the. structure; for example, the aerodynamic efficiency of an aircraft wing can be substantially reduced by only 1 to $1\frac{1}{2}\%$ deformation. The amount of ductility required for processing may far exceed that actually usable in service. Steel sheet, for example, often must have considerable ductility, far more than a part might need in service, but nevertheless enough to allow the part to be formed to its required shape.

Manufacturing Process Considerations

The properties considered in the preceding section relate to the ability of a material to perform adequately in service without failing. But, first the part must be capable of being made, that is it must be producible. There are additional properties and producibility considerations that should be part of the material selection process. For a design to be producible the configuration should not introduce unnecessarily difficult manufacturing challenges.

This section will briefly describe the key factors that influence the relationship between materials selection and processing. Reference 2 provides more detailed information on the characteristics of various manufacturing processes.

Material Factors

In a very general sense the selection of a material determines a range of processes that can be used to produce parts from the material. In the article "Introduction and Overview" in this Section, Fig. 4 shows the common classes of manufacturing processes and Table 4 indicates the manufacturing processes used most frequently with different metals and plastics. The melting point of a material and level of deformation resistance and ductility determine these relationships. Some materials are too brittle to be plastically deformed; other materials are too reactive to be cast or have poor weldability.

The melting point of a material determines the casting processes that can be employed. Low-melting-point metals can be used with any of a large number of casting processes, but as the melting point of the material rises, the number of available processes becomes limited. Ashby (Ref 3), has shown a correlation between the size (weight) of a cast part and the melting point of the material (Fig. 2). This plot shows the regions of size that can be handled by different casting and molding processes and shows how the available number of processes decreases dramatically for materials with high-melting point. This is one of a number of process selection charts, dealing with casting, metalworking, polymer processing, powder fabrication and machining, introduced by Ashby in Ref 3 to aid in the selection of manufacturing process in the conceptual stage of design.

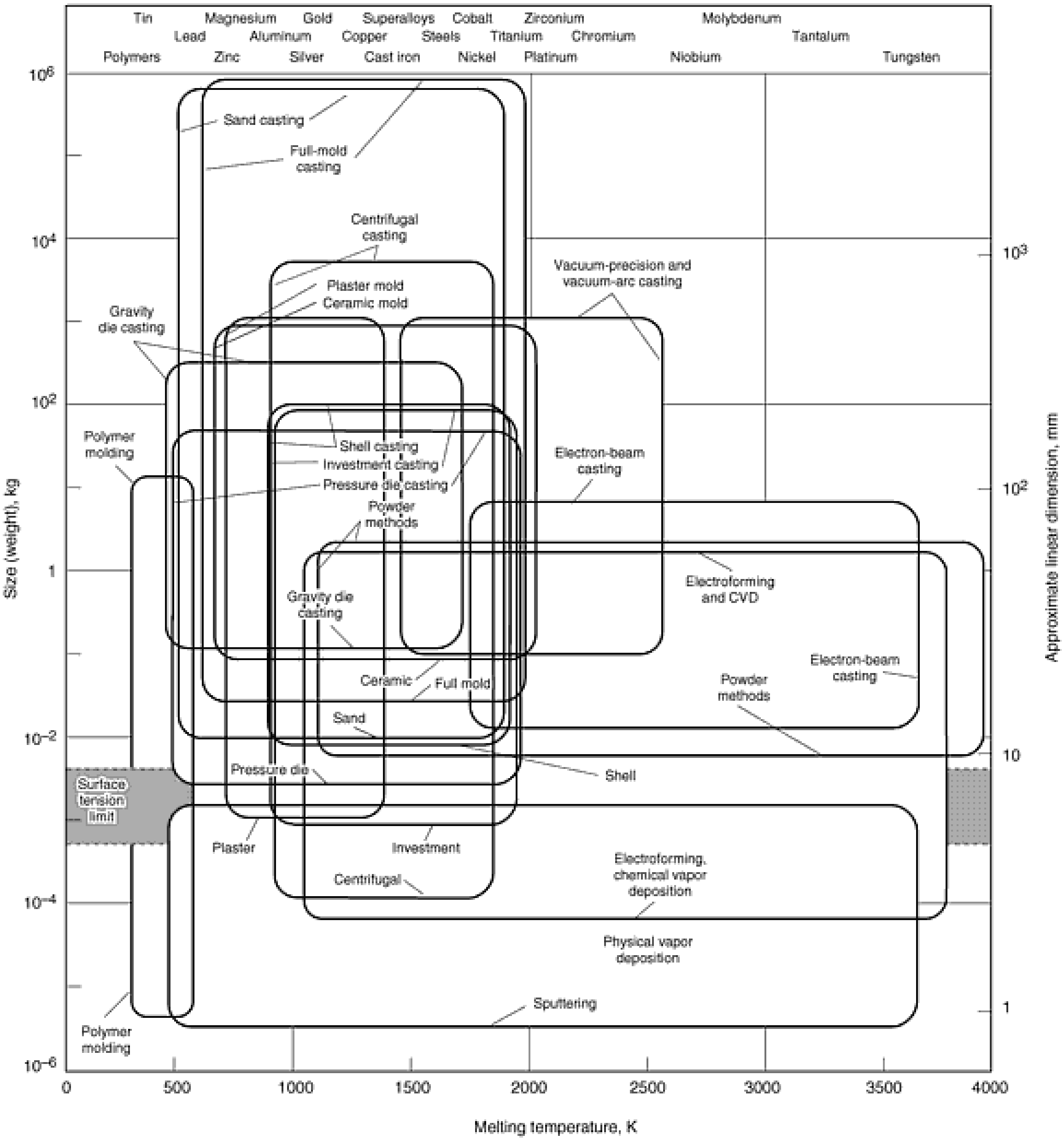

Fig. 2 Ashby process chart for casting. The size in this chart is measured by weight, *W*. It can be converted to volume via the density, ρ, or to the approximate linear dimension, *L*, shown on the right-hand axis via $L = (W/\rho)^{1/3}$. Source: Ref 3

Similarly, yield strength, or hardness, determines the limits in deformation and machining processes. Forging and rolling loads are related to yield strength and tool life (tool load and temperature generation) in machining scales with the hardness of the material being machined. Ultimately the limit of these processes is determined by the workability of the material. See the section "Fabricability" in this article.

Shape Factors

Each process has associated with it a range of shapes that can be produced. Thus, the first decision in selecting a process is whether it is capable of producing the required shape. A simple classification of shape is as follows:

Two-dimensional (2D)	Profile of product does not change along its length. Examples: wire, pipe, aluminum foil. Many 2D products are used as raw material for processes that make them into 3D shapes.
Three-dimensional (3D)	Profile of the product varies along all three axes. Most products are 3D.
Sheet	Has almost constant section thickness that is small compared with the other dimensions
Bulk	Has a complex shape, often with little symmetry. Solid: has no significant cavities. Hollow: has significant cavities

Whether the process can accommodate shapes with undercuts, or reentrant angles, or parts with an element positioned perpendicular to the main die motion also needs to be determined. For more in-depth considerations of shape and its relationship to process selection, see Ref 2.

Process Factors

Key manufacturing process factors include cycle time, quality, flexibility, materials utilization, and operating cost. A rating system for evaluating these five process characteristics is given in Table 3. This is applied to rating the most common manufacturing processes in Table 4.

Table 3 Scale for rating manufacturing processes

Rating	**Cycle time**	**Quality**	**Flexibility**	**Materials utilization**	**Operating costs**
1	>15 min	Poor quality, average reliability	Changeover extremely difficult	Waste > 100% of finished component	Substantial machine and tooling costs
2	5 to 15 min	Average quality	Slow changeover	Waste 50 to 100%	Tooling and machines costly
3	1 to 5 min	Average to good quality	Average changeover and setup time	Waste 10 to 50%	Tooling and machines relatively inexpensive
4	20 s to 1 min	Good to excellent quality	Fast changeover	Waste < 10% finished part	Tooling costs low/little equipment
5	<20 s	Excellent quality	No setup time	No appreciable waste	No setup costs

Rating scheme: 1, poorest; 5, best. Source: Ref 4

Table 4 Rating of characteristics for common manufacturing processes

Process	Shape	Cycle time	Flexibility	Material utilization	Quality	Equipment tooling costs
Casting						
Sand casting	3D	2	5	2	2	1
Evaporative foam	3D	1	5	2	2	4
Investment casting	3D	2	4	4	4	3
Permanent mold casting	3D	4	2	2	3	2
Pressure die casting	3D solid	5	1	4	2	1
Squeeze casting	3D	3	1	5	4	1
Centrifugal casting	3D hollow	2	3	5	3	3
Injection molding	3D	4	1	4	3	1
Reaction injection molding (RIM)	3D	3	2	4	2	2
Compression molding	3D	3	4	4	2	3
Rotational molding	3D hollow	2	4	5	2	4
Monomer casting, contact molding	3D	1	4	4	2	4
Forming						
Forging, open die	3D solid	2	4	3	2	2
Forging, hot-closed die	3D solid	4	1	3	3	2
Sheet metal forming	3D	3	1	3	4	1
Rolling	2D	5	3	4	3	2

Extrusion	2D	5	3	4	3	2
Superplastic forming	3D	1	1	5	4	1
Thermoforming	3D	3	2	3	2	3
Blow molding	3D hollow	4	2	4	4	2
Pressing and sintering	3D solid	2	2	5	2	2
Isostatic pressing	3D	1	3	5	2	1
Slip casting	3D	1	5	5	2	4
Machining						
Single-point cutting	3D	2	5	1	5	5
Multiple-point cut	3D	3	5	1	5	4
Grinding	3D	2	5	1	5	4
Electrical discharge machining	3D	1	4	1	5	1
Joining						
Fusion welding	All	2	5	5	2	4
Brazing/soldering	All	2	5	5	3	4
Adhesive bonding	All	2	5	5	3	5
Fasteners	3D	4	5	4	4	5
Surface treatment						
Shot peening	All	2	5	5	4	5
Surface hardening	All	2	4	5	4	4
CVD/PVD	All	1	5	5	4	3

2D, two dimensional; 3D, three dimensional. Rating scheme: 1, poorest; 5, best. Ratings from Ref 5

Cycle time is the time required to process one unit once the process has been set up and is operating properly. The inverse of cycle time is production rate.

Quality is an inclusive term describing fitness for use. Included under this characteristic is surface roughness, ability to manufacture parts to a set tolerance, product integrity (freedom from voids, pores, cracks, and inclusions), and ability to produce controlled properties (microstructure control).

Flexibility in manufacturing is the ease with a process can be adapted to produce different products or variations of the same product. In an era where product customization is becoming more important, this characteristic has gained importance. Flexibility is influenced greatly by the time to change and set up tooling.

Materials utilization measures the amount of material processed in addition to the material required in the product. Most machining operations generate 60 to 80% scrap. Net-shape forging and injection molding are at the other extreme. As materials costs become the greater part of the product cost, materials utilization becomes of greater importance.

Operating cost involves both the capital cost of plant, machinery, and tooling and the labor costs of setting up and running the process. Process selection often is constrained by the available equipment, particularly if the desired process is costly to install. In any manufacturing situation, one available decision is whether to outsource the production to a qualified subcontractor.

References cited in this section

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Fabricability

Fabricability, or ease of manufacture, describes the capability of a metal to be fabricated by various manufacturing processes. Such terms as formability, workability, castability, machinability, and weldability are implied by this topic.

Whenever possible, product design should incorporate those materials that can be readily fabricated using the desired process(es) without special precautions. Materials that can be fabricated by several methods offer convenient alternatives in the event unforeseen conditions suddenly preclude use of the principal fabrication method.

Questions regarding production, such as equipment and manufacturing capacity available for fabricating components, are directly related to fabricability, as is the quantity required. If several thousand duplicate parts are necessary, the high cost of dies or other specialized equipment for quantity production can be economically justified. If few pieces are required, hand production from relatively expensive materials in stock may be less expensive than use of more elaborate methods and less expensive materials. Even so, an engineering estimate should be made of the relation between product cost and quantity for each proposed production method.

Fabricability and mechanical properties are interrelated, and they quite often act in opposite directions. As strength levels are increased, often by increasing carbon or alloy content, weldability and machinability frequently decrease. Although most materials can be welded, higher-strength materials generally require special techniques; the designer must be aware of the added cost built into the part in order to meet the welding requirements. In some instances, there may be no practical method of regaining the strength of the base metal lost through welding. As machinability is increased by additions of sulfur or lead, long-life fatigue resistance is decreased.

In the remainder of this section, emphasis has been placed on the material characteristics that aid or hinder the production of a part without defects. Certain characteristics of a material are inherent in the selection of the manufacturing process;

for example, a molten metal that reacts strongly with the atmosphere would not be selected for casting in air. As will be described below, there are more subtle issues and materials selection tests that also need to be considered.

Castability

Castability deals with a complex combination of liquid-metal properties and solidification characteristics that promotes accurate and sound castings. The factors that influence castability are fluidity, shrinkage, and resistance to hot cracking.

Fluidity is the ability of liquid metal to run freely and fill a mold cavity. Because the viscosity of molten metals is very low, fluidity is determined more by the solidification dynamics of the metal and the mold. A high surface tension of the liquid metal reduces fluidity. Oxide films forming on the surface of the molten metal thus have a significantly adverse effect on fluidity. Insoluble inclusions also reduce fluidity. The pattern of solidification of the alloy is important. Fluidity is inversely related to the temperature range over which solidification occurs. Thus, pure metals and eutectic alloys, with short freezing range, have greater fluidity. Fluidity is usually evaluated by pouring the metal into a narrow spiral mold cavity and measuring the length of penetration of the metal before it solidifies.

Shrinkage is an important castability factor in deciding whether the alloy has a high tendency to form shrinkage porosity. Unfortunately, there is no standard test for shrinkage. For a discussion of how to control shrinkage porosity in casting design, see the Section on "Casting" in this Handbook.

Resistance to hot cracking is the ability of the alloy to withstand stresses developed by the contraction while cooling from the hot-short temperature range.

Castability is an integrated property that combines these three factors. One way to approach this is to rate the alloys on a scale of one to five for each of the important factors, use a weighting for the importance of each factor, and use a decision matrix to arrive at a ranking for each casting alloy (Ref 6). Table 5 shows typical applications for metal alloys and relative ratings with respect to castability, weldability, and machinability. Note that these are general overall ratings for a class of alloys. Within each class, different alloys vary considerably with respect to specific process characteristics.

Table 5 Typical applications for castings and general rating of castability, machinability, and weldability

Casting alloy type	Applications	Castability	Machinability	Weldability
Aluminum	Pistons, clutch housings, exhaust manifolds	1-2	1-2	3
Copper	Pumps, valves, marine propellors	1-3	1-2	3
Gray iron	Engine blocks, gears, brake disks and drums, machine bases	1	2	5
Magnesium	Crankcases, transmission housings	1-2	1	2
Malleable iron	Farm and construction machinery, heavy-duty bearings, railroad rolling stock	2	2	5
Nickel	Gas-turbine blades, pump and valve components for chemical plants	3	3	3
Nodular iron	Crankshafts, heavy-duty gears	2	2	5
Steel (carbon and low	Die blocks, heavy-duty gear blanks, railroad wheels	3	2-3	1

alloy)				
Steel (high alloy)	Gas-turbine housings, pump and valve components, rock-crusher jaws	3	3	1
White cast iron	Ball mill liners, shot-blasting nozzles, railroad brake shoes, crushers	2	4	4
Zinc	Door handles, radiator grilles, carburetor bodies	1	1	5

1, excellent; 2, good; 3, fair; 4, very poor; 5, difficult. Source: Ref 7

Workability and Formability

Two kinds of plastic deformation processes must be recognized. In three-dimensional, or bulk deformation, processes the material is deformed in all three principal directions. Here, the limit on deformation is concerned chiefly with the fracture of the material, and so ways to describe its workability are of interest. In two-dimensional, or sheet-forming, operations the deformation limit is caused by buckling, excessive thinning, or fracture; therefore, ways to describe the formability of the material are considered.

Workability is a complex technological concept that depends not only on the fracture resistance (ductility) of the material but also on the specific details (stress state) of the deformation process as determined by die geometry, work-piece geometry, and lubrication conditions. The greater the workability of a material the greater the deformation and/or the more complex the shape that can be produced before fracture occurs. Ease of manufacture also is aided when the material has a low-flow stress (yield strength) so that the force that must be applied by the processing equipment and the stresses on the dies are lower. Because flow stress decreases with increasing temperature, much plastic deformation of metals is carried out at elevated temperature (hot working).

Crack formation that limits workability is usually a form of ductile fracture. At temperatures lower than about one-half the melting point (absolute scale), this is the familiar dimple-rupture mode, but at higher temperature fracture initiated by grain-boundary sliding or cavitation can occur (Ref 8). Workability problems can also arise when deformation is localized to a narrow zone. Flow localization is caused by the formation of a dead-metal zone between the workpiece and the tooling, either because of poor lubrication or because the dies are cooler than the workpiece. Localized flow can also result from flow softening due to structural instabilities such as adiabatic heating, grain coarsening, or spheroidization.

The workability of a material is not a fixed material property. The state of stress in the workpiece imposed by the geometry of the deformation process greatly affects the workability. Stress states with high compressive components that impede crack initiation or propagation enhance workability. A general workability parameter, β, that corrects for stress state is given as (Ref 9):

$$\beta = \frac{3\sigma_m}{\bar{\sigma}} \quad \textbf{(Eq 1)}$$

where σ_m is the mean or hydrostatic component of stress:

$$\sigma_m = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \quad \textbf{(Eq 2)}$$

and σ is the effective stress:

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad \textbf{(Eq 3)}$$

Figure 3 shows the strain to fracture plotted against the parameter β. The curve is determined from three basic mechanical property tests: tension, torsion, and compression. The appropriate parameters for each of these tests are given in Table 6. Figure 3 also shows the location of the most common bulk metal deformation processes in terms of the level of compressive stress state.

Table 6 Evaluation of the workability parameter, β

Test	Principal stresses	Effective stress	Mean stress	β	Strain-to-fracture measurement
Tension	$\sigma_1:\sigma_2 = \sigma_3 = 0$	σ_1	$\sigma_1/3$	1.0	$\varepsilon_f = \ln (A_0/A_n)$ at necking
Torsion	$\sigma_1 = -\sigma_2; \sigma_3 = 0$	$\sqrt{3}\sigma_1$	0	0	$\varepsilon_f = (r\theta/\sqrt{3}L)$
Compression	$-\sigma_1; \sigma_2 = \sigma_3 = 0$	σ_1	$-\sigma_1/3$	-1.0	$\varepsilon_f = \ln (A_f/A_0)$

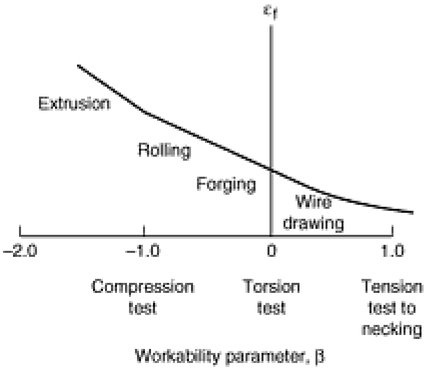


Fig. 3 Influence of stress state on strain to fracture. Source: Ref 8

One of the most successful and useful design tools to assess workability for free-surface fracture is the fracture locus diagram (Fig. 4) (Ref 10). The plot shows the locus of free-surface strains (one tensile and the other compressive) that cause fracture. These are obtained from tests on upset compression and bend-test specimens. For many metals the fracture locus is a straight line of slope $-\frac{1}{2}$. To use the fracture diagram, the calculated surface strains estimated to be developed during the deformation process are super-imposed on the fracture locus diagram. If the final strain for processing the part lies above the fracture line for the material, the part failure is expected. As shown in Fig. 4, a change to a material B with better workability or a change in the process conditions (lubrication, die design, or preform design) to reduce the level of surface tensile strain, for example, strain path b, can be made.

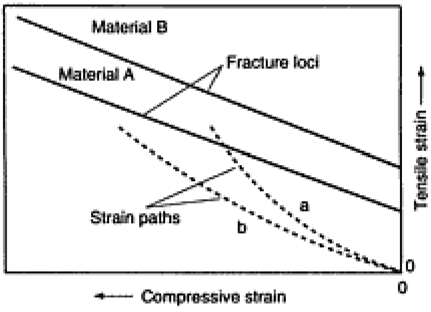


Fig. 4 Schematic workability diagram for bulk deformation processes. Strain path (a) would lead to failure for

material A. Both strain paths can be used for the successful forming of material B. Source: Ref 10

A large number of workability tests have been developed for bulk deformation processes (Ref 11, 12). In addition to the primary tests of tensile, upset compression, bend, and torsion, there are tests such as plane-strain compression, partial-width indentation, ring compression, and forgeability tests such as wedge forging, sidepressing, and the notched-bar upset tests. Some of these tests are further described in the Section on "Mechanical, Wear, and Corrosion Testing" in this Handbook.

Formability. The term formability is commonly used to describe the ability of a sheet metal to maintain its structural integrity while being plastically deformed into a shape. Failure can occur by tearing, buckling and wrinkling, or excessive thinning. An ideal material from the standpoint of formability should:

- Distribute the strain in the sheet uniformly (high *m*)
- Achieve high strain levels without necking or fracture (high *n*)
- Withstand in-plane compressive stresses without wrinkling
- Withstand in-plane shear stresses without fracturing
- Retain part shape on removal from the die
- Retain a smooth surface and resist surface damage

The strain distribution is determined by three material properties measured with the tensile test. The *strain-hardening exponent,* also known as the *n* value, is expressed as:

$$n = \frac{(\ln \sigma)}{d(\ln \varepsilon)} \qquad \textbf{(Eq 4)}$$

where σ is true stress and ϵ is true strain. The *strain-rate sensitivity,* also known as the *m* value, is expressed as:

$$m = \frac{d(\ln \sigma)}{d(\ln \dot{\varepsilon})} \qquad \textbf{(Eq 5)}$$

The *plastic strain ratio* (normal anisotropy), or *r* value, is expressed as:

$$r = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\ln (w/w_0)}{\ln(t/t_0)} \qquad \textbf{(Eq 6)}$$

where ϵ_w is the true strain in the width direction of the tensile specimen and ϵ_t is the true strain in its thickness direction.

The *r* value is a measure of the ability of the material to resist thinning while undergoing width reduction. A high *r* value is the measure of a material with good deep-drawing characteristics. High values of *n* and *m* lead to good formability in stretching operations because they promote uniform strain distribution, but they have little effect on drawability.

A forming limit diagram has been established for sheet metals by subjecting the sheet to various ratios of major to minor in-plane strains and plotting the locus of strain ratios for which local thinning (necking) and failure occur (Fig. 5). Strain conditions on the left side, where circles distort to ellipses, represent drawing conditions, while the right side where circles distort to larger circles corresponds to stretch conditions. When the minor strain is 0, a plane strain condition is developed. A forming limit diagram for a sheet metal can be used in conjunction with a trial run of the part to determine how close the material is to failure and how lubrication or die parameters should be adjusted to take the material away from a failure condition. The surface of the sheet is covered with a grid of circles produced by electrochemical marking. When the sheet is deformed, the grid of circles distort and the ratio of major to minor strain can be determined at critical points. These strains are plotted in Fig. 5 to determine how close the material is to failure.

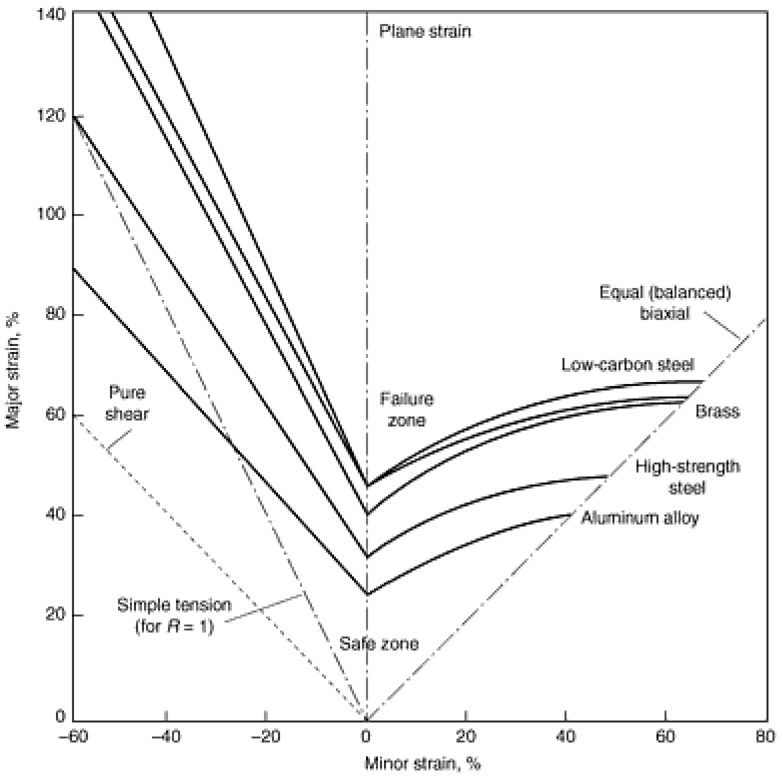


Fig. 5 Typical forming limit diagrams for different sheet metals. To use the diagram, locate the position on the chart for the major strain (always positive) and minor strain that is the most critical combination in the part to be formed. Failure will occur if the point is above the forming limit diagram for the sheet metal. Source: Ref 7

Many simulation tests for the formability of sheet metals have been developed (Ref 13). Olsen and Erichsen cup tests and the hemispherical dome tests measure stretching, while the Swift cup test measures drawing. The Swift round-bottomed test and the Fukui conical cup tests are involved with combined stretch and drawing. More detailed information on these test procedures is found in the Section on "Mechanical, Wear, and Corrosion Testing" in this Handbook.

Machinability

Machinability is the relative ease or difficulty of a material to be machined. A material has good machinability if the tool wear is low, the cutting forces are low, the chips break into small pieces instead of forming long snarls, and the surface finish is acceptable. This illustrates the problem of defining machinability as a characteristic material property. Machinability is more a system property that depends on the workpiece material plus the cutting tool material and its geometry, the type of machining operation, and the operating conditions of speed, feed, depth of cut, cutting tool geometry, nature of the cutting fluid, and the rigidity of the machine tool. The one material generalization that can be applied to machinability is that the higher the hardness of the workpiece material, the poorer the machinability. Even this fails at low hardness levels where soft, gummy materials develop chips with built-up edge and lower machinability. The requirement for the material to have good machinability varies with the machining operation (see Table 7).

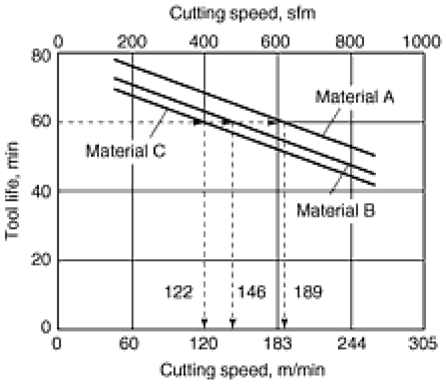
Table 7 Common machining processes listed in decreasing order of relative difficulty with respect to machinability of the workpiece

Internal broaching
External broaching
Tapping
Generation of gear teeth
Deep drilling
Boring
Screw machining with form tools
High-speed, light-feed screw machine operations
Milling

Shallow drilling
Planing and shaping
Turning with single-point tools
Sawing
Grinding

Source: Ref 14

The terms machinability index an machinability rating are used as qualitative and relative measures of the machinability of a material under specified cutting conditions. This concept was introduced early in this century when high-speed steel tools dominated the field. The tool life obtained in turning B1112 resulfurized steel with a high-speed steel tool at 180 sfm was assigned a machinability rating of 100. Suppose the tool lasted for 60 min. If in another steel the identical tool lasted for 40 min, then this material would be given a machinability rating of $\left(\frac{40}{60}\right)$ 100 = 67. Because small changes in cutting speed produce large changes in tool life, it is more practical to measure machinability as the cutting speed that causes tool failure in a specified time period, usually 60 min. This makes use of the Taylor tool life equation; the cutting speed times tool life raised to an exponent equals a constant, (VT^n = C). Figure 6 shows the plot and method of determining the machinability exponent.



Material	Casting speed for 60 min tool life		Machinability rating
	m/min	sfm	
A	189	620	100
B	146	480	77 $\left(\frac{146}{189}\right) \times 100$
C	122	400	65 $\left(\frac{122}{189}\right) \times 100$

Fig. 6 Relationship between tool life and cutting speed based on Taylor equation. Table shows how the machinability rating would be determined. Source: Ref 15

Surface finish is another criterion for evaluating machinability. The better the surface finish under a given set of conditions, the higher the machinability of the material. Similarly, cutting force tests to measure the feed force under a given set of conditions are sometimes used. The most fundamental measure of machinability is the energy consumed in machining a unit volume of material (Ref 16). See Table 8 for some values. For details on conducting machinability tests, see Ref 14, 15, and 18.

Table 8 Approximate energy per unit volume requirements for machining different metals and alloys

Material	**Hardness, HB**	**Unit energy[(a)], (W/s)/mm^3**
Aluminum	50-100	0.55
Aluminum alloys	100-150	0.65
Cast irons	125-175	0.87
	175-250	1.3
Carbon steel	150-200	1.3
	200-250	1.7
	250-300	2.2
Alloy steel	200-250	1.7
	250-300	2.2
	300-350	2.8
	350-400	3.5
Copper	. . .	1.5
Brass	100-150	1.7
Bronze	100-150	1.7
High-temperature alloys	. . .	3.3-8.5
Titanium alloys	. . .	3.0-4.1
Refractory metals	. . .	3.8-9.3

Source: Ref 16, 17

(a) To convert unit energy to (hp/min)/in.^{3} divide by 2.73.

Microstructure can have an important influence on machinability. Spheroidized carbides are more machinable than pearlite platelets. Control of the inclusions in steel through small additions of sulfur, phosphorus, or calcium can be decisive. The influence of the manufacturing process on machinability is exemplified with the aluminum-silicon casting alloy, A390. Castings made by conventional die casting are more machinable than those produced by sand casting. This is attributable to the microstructure resulting from widely differing cooling rates. The die-casting process produces very fine, evenly distributed silicon particles, while the sand casting has larger silicon particles that are less uniformly distributed.

Finally, it needs to be understood that machinability data show considerable scatter. For B1112 steel, within the composition range permitted by that grade, it was found that the machinability index varied as much as 20% below and 60% above the nominal value of 100 assigned to this grade because of unintentional variations in carbon, sulfur, and silicon content. In general, differences of 5% in machinability ratings are not likely to be significant or reproducible.

Weldability

The weldability of a particular metal combination describes the ease with which the weld can be made and the quality and soundness of that weld. All metals can be welded to themselves by at least one of the welding processes (Table 9); these processes are discussed in the Section on "Joining" in this Volume. The primary factor that controls weldability is the composition of the base metal and the filler metal. A fusion weld cannot be made between dissimilar metals unless they have metallurgical solubility. Barring this, brittle compounds may be formed. Weldability is affected by such defects as cracking in the weld metal, porosity, or cracking in the heat-affected zone (HAZ). Weld cracking in steel can be caused by the presence of very small amounts of hydrogen, the formation of martensite in the weld, and the presence of high-residual stresses. Free-machining steel with high-sulfur content cannot be fusion welded without cracking due to hot shortness. Hardenable steels must be welded with caution to avoid brittle martensite formation. Preheating the weld to reduce the quench rate and postheating to temper any martensite should be practiced. To estimate whether hardenability problems are likely to affect weldability of a steel, the carbon equivalent *CE,* is determined:

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Ni}{15} + \frac{\%Cu}{15} + \frac{\%Cr}{5} + \frac{\%Mo}{5} + \frac{\%V}{5} \qquad \textbf{(Eq 7)}$$

When the *CE* of a steel is less than 0.45%, weld cracking is unlikely and no heat treatment is required.

Table 9 Weldability of specific metals and alloys

Base metals welded	**Welding processes**								
	Shielded metal arc	**Gas tungsten arc**	**Plasma arc**	**Submerged arc**	**Gas metal arc**	**Flux-cored arc**	**Electroslag**	**Braze**	**Gas**
Aluminum	C	A	A	No	A	No	Exp	B	B
Copper-base alloys									

Brasses	No	C	C	No	C	No	No	A	A
Bronzes	A	A	B	No	A	No	No	A	B
Copper	C	A	A	No	A	No	No	A	A
Copper nickel	B	A	A	No	A	No	No	A	A
Nickel silver (Cu-Ni-Zn)	No	C	C	No	C	No	No	A	B
Irons									
Cast, malleable nodular	C	No	No	No	C	No	No	A	A
Wrought iron	A	B	B	A	A	A	No	A	A
Lead	No	B	B	No	No	No	No	No	A
Magnesium	No	A	B	No	A	No	No	No	No
Nickel-base alloys									
Inconel	A	A	A	No	A	No	No	A	B
Nickel	A	A	A	C	A	No	No	A	A
Monel	A	A	A	C	A	No	No	A	A
Precious metals	No	A	A	No	No	No	No	A	B
Steels									
Low-carbon steel	A	A	A	A	A	A	A	A	A
Low-alloy steel	B	B	B	B	B	B	A	A	A
High- and medium-carbon steel	C	C	C	B	C	C	A	A	A
Alloy steel	C	C	C	C	C	C	A	A	A

Stainless steel (austenitic)	A	A	A	A	A	B	A	A	C
Tool steels	No	C	C	No	No	No	No	A	A
Titanium	No	A	A	No	A	No	No	No	No
Tungsten	No	B	A	No	No	No	No	No	No
Zinc	No	C	C	No	No	No	No	No	C

Metal or process rating: A, recommended or easily weldable; B, acceptable but not best selection or weldable with precautions; C, possibly usable but not popular or restricted use or difficult to weld; No, not recommended or not weldable. Source: Ref 19

The quality of welds is determined from a variety of tests. Tension and bend tests of specimens containing the weld are commonly used. A variety of drop weight and fracture toughness tests are used with steel welds. A large number of tests have been developed for determining the susceptibility of the weld joint to cracking during fabrication. These can be divided into restraint tests, externally loaded tests, underbead cracking tests, and lamellar tearing tests (Ref 20). These tests are also described in the Section "Joining" in this Handbook.

Heat Treatability

Satisfactory response to heat treatment is the capability of a material, fashioned into a particular part, to be heat treated to a desired microstructure, hardness, and strength level without undergoing cracking, distortion, or excessive size change, that is, the heat treatability of the material. The most important factors affecting response to heat treatment are the recrystallization, phase-decomposition, and/or transformation characteristics of the material, the configuration and mass of the part, and control of the heat treating operation.

Before determining what response to heat treatment is needed for a particular application, it is important to determine that heat treatment is absolutely necessary. The economy that may be realized by eliminating heat treatment can be considerable, but is often neglected due to the automatic assumption that a part--particularly a steel part--will be heat treated.

Because heat treatment can create substantial thermal stresses in the part (even if the part is not quenched), the part should be designed so that the deleterious effects of these thermal stresses are minimized; thermal stresses are greatest during quenching. The basic objective is to design the part so that the temperature distribution during heating and cooling is as uniform as possible. Sharp corners, particularly internal corners, must be avoided, because they concentrate thermal stresses, thus accentuating their effect on the part. The largest possible radii should be used in corners. Uniform section thickness facilitates uniform temperature distribution. Designing a part to minimize thermal stresses during heat treatment usually permits choice of the least costly material that can provide the required properties.

Perhaps the most common heat treatment is the austenitize, quench, and temper sequence, which is the dominant process for hardening carbon and alloy steels. The critical aspect of this sequence is that the hardened steel part must contain a minimum percentage of martensite in order to meet the specified hardness. In other words, the hardenability of the steel must be sufficient to provide that percentage of martensite when the part is quenched into a medium that is appropriate to the size, shape, and distortion tolerance of the part.

To achieve particular combinations of mechanical properties, it may be necessary to specify other heat treatments, such as austempering, induction hardening, flame hardening, carburizing, or nitriding. Each of these processes places certain restrictions on the choice of steel; the restrictions may include carbon content, hardenability, or the need for certain alloying elements.

Seemingly minor changes in the heat treating operation can often produce significant reductions in manufacturing costs, particularly if the change reduces the scrap rate, permits a change to a less costly alloy, or facilitates a subsequent fabricating operation.

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Other Major Factors in Materials Selection

Design Configuration. The shape of an object is partly responsible for service demands placed on the material from which it is made. Cross-sectional dimensions, for example, may determine the stresses imposed on the material by service loads. These apparent stresses may be increased through the effects of notches and changes in section size. Design configuration determines whether or not a component will be subjected to particular hazards, such as wear or exposure to a corrosive environment. It may also determine the product form from which the item is made. A long, slender part is often made from strip or bar simply because the raw material has the same general shape. A part with a high degree of rotational symmetry is often turned on a lathe. A hollow sphere can be made by joining two hemispheres stamped from flat sheet.

Available and Alternative Materials. Regardless of the merits of a material for a given application, if that material is not readily available in the desired form and quantity, it is a poor choice for that application. The question of material availability is compounded by shortages caused by market fluctuations, political instability in the ore/metal-producing source, inability or reluctance of producers to supply the desired material in the desired form or quantity, and changes in the relative costs of various materials. A further complication may exist if a particular part is made in several locations, especially if these locations are in different countries. Thus, it is desirable to select more than one material for an application and, if possible, to give an order of preference.

Sometimes, an alternative material will be necessary as a substitute for a preferred but unavailable material. In other instances, the alternative material will be selected because of superiority in the specific situation. For example, a tool manufacturer had been purchasing AISI 1078 and 1086 carbon steel bars, which have overlapping composition ranges. This manufacturer decided to use only 1078 and thus reduce his inventory. Even more important, because it is a more widely used grade, 1078 is produced more frequently than 1086, and thus is more available and easier to schedule.

An alternative material for a pressure vessel may have slightly greater strength than a material it can replace. Even a small increase in strength, however, can mean a significant reduction in wall thickness. It also may permit fabrication of slightly larger vessels. The pressure-vessel designer, however, must be sure that the increase in strength does not concurrently reduce fracture resistance below acceptable values.

The desired form can also cause availability problems. A material that can be obtained only in castings obviously cannot readily be used in applications requiring drawn tubing, extrusions, wire cloth, or other fabricated shapes.

Corrosion and Degradation in Service. A material can be regarded as either resistant or susceptible to corrosion and degradation in service, depending on the nature of the application. Sometimes, it may be preferable to use a low-cost, frequently replaced component and assume that it will be corroded or degraded in a short time; in other situations, however, this approach may not be acceptable because of high potential danger to personnel or for other reasons.

There are other factors that should be considered when dealing with corrosive media, because neglect of these can lead to erroneous interpretations of corrosion tests and handbook data:

- A sample in a simple static test at a given temperature may corrode in a manner and at a rate significantly different than if the material were simultaneously transferring heat to the corrosive medium or if there were significant relative movement between the material and the corrosive medium.
- The test medium can become contaminated during the experiment, and its corrosive characteristics may change.
- Lack of correlation between laboratory tests and operating conditions may be caused by a limited ratio of solution volume to surface area of test material in the laboratory test.
- Pressure of gas or vapor above a corrosive liquid can appreciably affect the amounts of oxygen or other gases that may be dissolved in the solution.
- Alloys that owe their corrosion resistance to development of passive films are particularly susceptible to development of concentration cells.
- The ability of the material to withstand stress-corrosion cracking or corrosion fatigue in service is not always accurately predicted by standard laboratory tests for these qualities. If the material is, in fact, susceptible to either failure process in the service environment, sudden and unpredictable service failures can occur because cracks propagate so rapidly under the combined action of stress and corrosion.

Stability of material in service can be affected by temperature, fluctuations in temperature, length of time at temperature, and, in some applications, exposure to radiation. Elevated temperature not only reduces strength and induces creep but also can produce changes in microstructure, such as tempering of martensitic steels and overaging of precipitation-hardening alloys. Obviously, duration of exposure is important in determining the extent to which these phenomena occur and, consequently, in determining appropriate stability requirements. A rocket motor, for instance, may be required to operate only briefly, whereas a steam turbine is expected to operate for many years. In many applications, it is essential to avoid any and all failures that would require the equipment to be shut down for repairs. In others, especially those involving mechanical wear, replacement at regular intervals is anticipated, and the affected part is designed to be readily replaced.

Other aspects of stability are the consequences of failure. For instance, a leak in a teakettle may be only a nuisance, but a leak in a vessel containing a flammable or radioactive fluid is critical. It should be noted that many designs for long-term operation involve extrapolation or educated guessing because the best available data typically represent lifetimes much shorter than those anticipated in actual service. The need for conservatism in design for such service should be obvious.

Properties of Unique Interest. For most problems in materials selection, the choice represents a compromise among a large number of properties and fabrication characteristics of the material; each of these properties and fabrication characteristics has a significant effect on final choice. Often, however, one or two properties are far more important than all others. Some examples of applications where a single property of unique interest dominates the selection of a material are:

- *High density:* gyroscope rotors and winding weights in self-winding watches
- *High stiffness-to-weight ratio:* aircraft frame components
- *Low melting point:* fusible links in sprinkler systems and fire doors
- *Expansion during freezing:* type metal
- *Special thermal-expansion characteristics:* metal-to-glass seals
- *Electrical conductivity (including superconductivity):* power-distribution systems
- *Wear resistance:* many applications, from plowshares and ore-crusher jaws to gear teeth and cam surfaces.
- *Biocompatibility:* prosthetic devices and dental implants/alloys

These are only a few examples of applications where a requirement for one or two properties of special interest severely limits the number of candidate materials. More detailed information on such materials can be found in the Section "Special-Purpose Materials" in this Handbook.

A requirement for a particular combination of properties further limits the number of candidate materials. Beryllia (BeO) conducts heat as well as aluminum alloys but is an electrical insulator, the only known material with high thermal and low electrical conductivities. For applications demanding high toughness at low temperatures, the choice of materials is limited to metals with face-centered-cubic lattices and certain high-nickel steels. Turbine blades in the hot stages of gas turbine engines must resist deformation and corrosion at operating temperatures and must not fail in thermal fatigue.

Cost. In almost every situation, final selection of a material for a specific application depends on a compromise. In some applications, there are specialized requirements that restrict the choice to relatively few materials. Even then, there is a compromise among the contending factors. The compromise and final selection also involve economic considerations. Initial cost of a piece of equipment involves raw-material, fabrication, assembly, and installation costs. Although the cost of material has a major influence on the cost of a manufactured part--60% of the cost of manufactured goods according to Ref 21--it is generally a relatively small part of the total life-cycle cost of the equipment. After the equipment has been placed in service, there may be additional costs, such as required rate of return on investment, depreciation, taxes, product-liability costs, replacements due to failure, shutdown expenses when equipment is undergoing repair or replacement, and production loss.

No industry is immune to savings through more effective application of materials. At least three major approaches may be taken to reduce cost through better use: (1) reconsider the material and mill form selected, (2) reconsider the shape of the part and its method of fabrication, and (3) redesign to take full advantage of properties. Although these apply primarily to production-line parts rather than tailor-made parts, the philosophy is applicable to all products.

In many situations, definite savings can be realized by the simple expedient of changing from one material to another without substantially changing the form or processing procedure. There are other applications for which two or more materials can be considered as alternates, with the choice at any given time dictated by current market prices.

Great savings can often be realized by changing the fabrication procedure or form in which material is used. One prominent example is the automobile-engine crankshaft. For many years, crankshafts were machined from forged steel that had to meet rather stringent specifications of strength and toughness. However, high toughness is an unnecessary requirement because a bent crankshaft is just as useless as a broken crankshaft, and impact loading on a crankshaft is not severe. Realization of these facts made it possible to effect a change to cast crankshafts. Today, there are millions of cast crankshafts in successful operation, all incapable of appreciable plastic bending, but having adequate rigidity and wear resistance. The cost of a cast and machined crankshaft is significantly less than that of a forged and machined crankshaft.

Structure/Property Relationships in Irons and Steels

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Introduction

THE PROPERTIES of irons and steels are linked to the chemical composition, processing path, and resulting microstructure of the material; this correspondence has been known since the early part of the twentieth century. For a particular iron and steel composition, most properties depend on microstructure. These properties are called structure-sensitive properties, for example, yield strength and hardness. The structure-insensitive properties, for example, electrical conductivity, are not discussed in this Section. Processing is a means to develop and control microstructure, for example, hot rolling, quenching, and so forth. In this Section, the role of these factors is described in both theoretical and practical terms, with particular focus on the role of microstructure.

Basis of Material Selection

In order to select a material for a particular component, the designer must have an intimate knowledge of what properties are required. Consideration must be given to the environment (corrosive, high temperature, etc.) and how the component will be fabricated (welded, bolted, etc.). Once these property requirements are established the material selection process can begin. Some of the properties to be considered are:

Mechanical properties

- **Strength**
  - Tensile strength (ultimate strength)
  - Yield strength
  - Compressive strength
- **Hardness**
- **Toughness**
  - Notch toughness
  - Fracture toughness
- **Ductility**
  - Total elongation
  - Reduction in area
- **Fatigue resistance**

Other properties/characteristics

- Formability
  - Drawability

Stretchability
Bendability

Wear resistance

Abrasion resistance
Galling resistance
Sliding wear resistance
Adhesive wear resistance

Machinability
Weldability

Table 1 lists mechanical properties of selected steels in various heat-treated or cold-worked conditions.

Table 1 Mechanical properties of selected steels

Steel	**Condition**	**Tensile strength**		**Yield strength**		**Elongation in 50 mm, %**	**Reduction in area, %**	**Hardness, HB**
		MPa	**ksi**	**MPa**	**ksi**			
Carbon steel bar[(a)]								
1006	Hot rolled	295	43	165	24	30	55	86
	Cold drawn	330	48	285	41	20	45	95
1008	Hot rolled	305	44	170	24.5	30	55	86
	Cold drawn	340	49	285	41.5	20	45	95
1010	Hot rolled	325	47	180	26	28	50	95
	Cold drawn	365	53	305	44	20	40	105
1012	Hot rolled	330	48	185	26.5	28	50	95
	Cold drawn	370	54	310	45	19	40	105
1015	Hot rolled	345	50	190	27.5	28	50	101
	Cold drawn	385	56	325	47	18	40	111

1016	Hot rolled	380	55	205	30	25	50	110
	Cold drawn	420	61	350	51	18	40	121
1017	Hot rolled	365	53	200	29	26	50	105
	Cold drawn	405	59	340	49	18	40	116
1018	Hot rolled	400	58	220	32	25	50	116
	Cold drawn	440	64	370	54	15	40	126
1019	Hot rolled	405	59	225	32.5	25	50	116
	Cold drawn	455	66	380	55	15	40	131
1020	Hot rolled	380	55	205	30	25	50	111
	Cold drawn	420	61	350	51	15	40	121
1021	Hot rolled	420	61	230	33	24	48	116
	Cold drawn	470	68	395	57	15	40	131
1022	Hot rolled	425	62	235	34	23	47	121
	Cold drawn	475	69	400	58	15	40	137
1023	Hot rolled	385	56	215	31	25	50	111
	Cold drawn	425	62	360	52.5	15	40	121
1524	Hot rolled	510	74	285	41	20	42	149
	Cold drawn	565	82	475	69	12	35	163
1025	Hot rolled	400	58	220	32	25	50	116
	Cold drawn	440	64	370	54	15	40	126
1026	Hot rolled	440	64	240	35	24	49	126

	Cold drawn	490	71	415	60	15	40	143
1527	Hot rolled	515	75	285	41	18	40	149
	Cold drawn	570	83	485	70	12	35	163
1030	Hot rolled	470	68	260	37.5	20	42	137
	Cold drawn	525	76	440	64	12	35	149
1035	Hot rolled	495	72	270	39.5	18	40	143
	Cold drawn	550	80	460	67	12	35	163
1536	Hot rolled	570	83	315	45.5	16	40	163
	Cold drawn	635	92	535	77.5	12	35	187
1037	Hot rolled	510	74	280	40.5	18	40	143
	Cold drawn	565	82	475	69	12	35	167
1038	Hot rolled	515	75	285	41	18	40	149
	Cold drawn	570	83	485	70	12	35	163
1039	Hot rolled	545	79	300	43.5	16	40	156
	Cold drawn	605	88	510	74	12	35	179
1040	Hot rolled	525	76	290	42	18	40	149
	Cold drawn	585	85	490	71	12	35	170
1541	Hot rolled	635	92	350	51	15	40	187
	Cold drawn	705	102.5	600	87	10	30	207
	Annealed, cold drawn	650	94	550	80	10	45	184
1042	Hot rolled	550	80	305	44	16	40	163

	Cold drawn	615	89	515	75	12	35	179
	Normalized, cold drawn	585	85	505	73	12	45	179
1043	Hot rolled	565	82	310	45	16	40	163
	Cold drawn	625	91	530	77	12	35	179
	Normalized, cold drawn	600	87	515	75	12	45	179
1044	Hot rolled	550	80	305	44	16	40	163
1045	Hot rolled	565	82	310	45	16	40	163
	Cold drawn	625	91	530	77	12	35	179
	Annealed, cold drawn	585	85	505	73	12	45	170
1046	Hot rolled	585	85	325	47	15	40	170
	Cold drawn	650	94	545	79	12	35	187
	Annealed, cold drawn	620	90	515	75	12	45	179
1547	Hot rolled	650	94	360	52	15	30	192
	Cold drawn	710	103	605	88	10	28	207
	Annealed, cold drawn	655	95	585	85	10	35	187
1548	Hot rolled	660	96	365	53	14	33	197
	Cold drawn	735	106.5	615	89.5	10	28	217
	Annealed, cold drawn	645	93.5	540	78.5	10	35	192
1049	Hot rolled	600	87	330	48	15	35	179
	Cold drawn	670	97	560	81.5	10	30	197
	Annealed, cold drawn	635	92	530	77	10	40	187

1050	Hot rolled	620	90	340	49.5	15	35	179
	Cold drawn	690	100	580	84	10	30	197
	Annealed, cold drawn	655	95	550	80	10	40	189
1552	Hot rolled	745	108	410	59.5	12	30	217
	Annealed, cold drawn	675	98	570	83	10	40	193
1055	Hot rolled	650	94	355	51.5	12	30	192
	Annealed, cold drawn	660	96	560	81	10	40	197
1060	Hot rolled	675	98	370	54	12	30	201
	Spheroidized annealed, cold drawn	620	90	485	70	10	45	183
1064	Hot rolled	670	97	370	53.5	12	30	201
	Spheroidized annealed, cold drawn	615	89	475	69	10	45	183
1065	Hot rolled	690	100	380	55	12	30	207
	Spheroidized annealed, cold drawn	635	92	490	71	10	45	187
1070	Hot rolled	705	102	385	56	12	30	212
	Spheroidized annealed, cold drawn	640	93	495	72	10	45	192
1074	Hot rolled	725	105	400	58	12	30	217
	Spheroidized annealed, cold drawn	650	94	505	73	10	40	192
1078	Hot rolled	690	100	380	55	12	30	207
	Spheroidized annealed, cold drawn	650	94	500	72.5	10	40	192
1080	Hot rolled	770	112	425	61.5	10	25	229
	Spheroidized annealed, cold drawn	675	98	515	75	10	40	192

1084	Hot rolled	820	119	450	65.5	10	25	241
	Spheroidized annealed, cold drawn	690	100	530	77	10	40	192
1085	Hot rolled	835	121	460	66.5	10	25	248
	Spheroidized annealed, cold drawn	695	100.5	540	78	10	40	192
1086	Hot rolled	770	112	425	61.5	10	25	229
	Spheroidized annealed, cold drawn	670	97	510	74	10	40	192
1090	Hot rolled	840	122	460	67	10	25	248
	Spheroidized annealed, cold drawn	695	101	540	78	10	40	197
1095	Hot rolled	825	120	455	66	10	25	248
	Spheroidized annealed, cold drawn	680	99	525	76	10	40	197
1211	Hot rolled	380	55	230	33	25	45	121
	Cold drawn	515	75	400	58	10	35	163
1212	Hot rolled	385	56	230	33.5	25	45	121
	Cold drawn	540	78	415	60	10	35	167
1213	Hot rolled	385	56	230	33.5	25	45	121
	Cold drawn	540	78	415	60	10	35	167
12L14	Hot rolled	395	57	235	34	22	45	121
	Cold drawn	540	78	415	60	10	35	163
1108	Hot rolled	345	50	190	27.5	30	50	101
	Cold drawn	385	56	325	47	20	40	121
1109	Hot rolled	345	50	190	27.5	30	50	101

	Cold drawn	385	56	325	47	20	40	121
1117	Hot rolled	425	62	235	34	23	47	121
	Cold drawn	475	69	400	58	15	40	137
1118	Hot rolled	450	65	250	36	23	47	131
	Cold drawn	495	72	420	61	15	40	143
1119	Hot rolled	425	62	235	34	23	47	121
	Cold drawn	475	69	400	58	15	40	137
1132	Hot rolled	570	83	315	45.5	16	40	167
	Cold drawn	635	92	530	77	12	35	183
1137	Hot rolled	605	88	330	48	15	35	179
	Cold drawn	675	98	565	82	10	30	197
1140	Hot rolled	545	79	300	43.5	16	40	156
	Cold drawn	605	88	510	74	12	35	170
1141	Hot rolled	650	94	355	51.5	15	35	187
	Cold drawn	725	105.1	605	88	10	30	212
1144	Hot rolled	670	97	365	53	15	35	197
	Cold drawn	745	108	620	90	10	30	217
1145	Hot rolled	585	85	325	47	15	40	170
	Cold drawn	650	94	550	80	12	35	187
1146	Hot rolled	585	85	325	47	15	40	170
	Cold drawn	650	94	550	80	12	35	187

1151	Hot rolled	635	92	350	50.5	15	35	187
	Cold drawn	705	102	595	86	10	30	207
Low-alloy steels(b)								
1340	Normalized at 870 °C (1600 °F)	834	121	558	81	22.0	63	248
	Annealed at 800 °C (1475 °F)	703	102	434	63	25.5	57	207
3140	Normalized at 870 °C (1600 °F)	889	129	600	87	19.7	57	262
	Annealed at 815 °C (1500 °F)	690	100	420	61	24.5	51	197
4130	Normalized at 870 °C (1600 °F)	670	97	435	63	25.5	59.5	197
	Annealed at 865 °C (1585 °F)	560	81	460	67	21.5	59.6	217
	Water quenched from 855 °C (1575 °F) and tempered at 540 °C (1000 °F)	1040	151	979	142	18.1	63.9	302
4140	Normalized at 870 °C (1600 °F)	1020	148	655	95	17.7	46.8	302
	Annealed at 815 °C (1500 °F)	655	95	915	60	25.7	56.9	197
	Water quenched from 845 °C (1550 °F) and tempered at 540 °C (1000 °F)	1075	156	986	143	15.5	56.9	311
4150	Normalized at 870 °C (1600 °F)	1160	168	731	106	11.7	30.8	321
	Annealed at 830 °C (1525 °F)	731	106	380	55	20.2	40.2	197
	Oil quenched from 830 °C (1525 °F) and tempered at 540 °C (1000 °F)	1310	190	1215	176	13.5	47.2	375
4320	Normalized at 895 °C (1640 °F)	793	115	460	67	20.8	51	235
	Annealed at 850 °C (1560 °F)	580	84	425	62	29.0	58	163
4340	Normalized at 870 °C (1600 °F)	1282	186	862	125	12.2	36.3	363
	Annealed at 810 °C (1490 °F)	745	108	470	68	22.0	50.0	217

	Oil quenched from 800 °C (1475 °F) and tempered at 540 °C (1000 °F)	1207	175	1145	166	14.2	45.9	352
4419	Normalized at 955 °C (1750 °F)	515	75	350	51	32.5	69.4	143
	Annealed at 915 °C (1675 °F)	450	65	330	48	31.2	62.8	121
4620	Normalized at 900 °C (1650 °F)	570	83	365	53	29.0	66.7	174
	Annealed at 855 °C (1575 °F)	510	74	370	54	31.3	60.3	149
4820	Normalized at 860 °C (1580 °F)	758	110	485	70	24.0	59.2	229
	Annealed at 815 °C (1500 °F)	685	99	460	67	22.3	58.8	197
5140	Normalized at 870 °C (1600 °F)	793	115	470	68	22.7	59.2	229
	Annealed at 830 °C (1525 °F)	570	83	290	42	28.6	57.3	167
	Oil quenched from 845 °C (1550 °F) and tempered at 540 °C (1000 °F)	972	141	841	122	18.5	58.9	293
5150	Normalized at 870 °C (1600 °F)	869	126	530	77	20.7	58.7	255
	Annealed at 825 °C (1520 °F)	675	98	360	52	22.0	43.7	197
	Oil quenched from 830 °C (1525 °F) and tempered at 540 °C (1000 °F)	1055	159	1000	145	16.4	52.9	311
5160	Normalized at 855 °C (1575 °F)	1025	149	650	94	18.2	50.7	285
	Annealed at 815 °C (1495 °F)	724	105	275	40	17.2	30.6	197
	Oil quenched from 830 °C (1525 °F) and tempered at 540 °C (1000 °F)	1145	166	1005	146	14.5	45.7	341
6150	Normalized at 870 °C (1600 °F)	938	136	615	89	21.8	61.0	269
	Annealed at 815 °C (1500 °F)	670	97	415	60	23.0	48.4	197
	Oil quenched from 845 °C (1550 °F) and tempered at 540 °C (1000 °F)	1200	174	1160	168	14.5	48.2	352

8620	Normalized at 915 °C (1675 °F)	635	92	360	52	26.3	59.7	183
	Annealed at 870 °C (1600 °F)	540	78	385	56	31.3	62.1	149
8630	Normalized at 870 °C (1600 °F)	650	94	425	62	23.5	53.5	187
	Annealed at 845 °C (1550 °F)	565	82	370	54	29.0	58.9	156
	Water quenched from 845 °C (1550 °F) and tempered at 540 °C (1000 °F)	931	135	850	123	18.7	59.6	269
8650	Normalized at 870 °C (1600)	1025	149	690	100	14	45.0	302
	Annealed at 795 °C (1465 °F)	715	104	385	56	22.5	46.0	212
	Oil quenched from 800 °C (1475 °F) and tempered at 540 °C (1000 °F)	1185	172	1105	160	14.5	49.1	352
8740	Normalized at 870 °C (1600 °F)	931	135	605	88	16.0	47.9	269
	Annealed at 815 °C (1500 °F)	696	101	415	60	22.2	46.4	201
	Oil quenched from 830 °C (1525 °F) and tempered at 540 °C (1000 °F)	1225	178	1130	164	16.0	53.0	352
9255	Normalized at 900 °C (1650 °F)	931	135	580	84	19.7	43.4	269
	Annealed at 845 °C (1550 °F)	779	113	485	70	21.7	41.1	229
	Oil quenched from 885 °C (1625 °F) and tempered at 540 °C (1000 °F)	1130	164	924	134	16.7	38.3	321
9310	Normalized at 890 °C (1630 °F)	910	132	570	83	18.8	58.1	269 HRB
	Annealed at 845 °C (1550 °F)	820	119	450	65	17.3	42.1	241 HRB
Ferritic stainless steels[(b)]								
405	Annealed bar	483	70	276	40	30	60	150
	Cold drawn bar	586	85	483	70	20	60	185

409	Annealed bar	450	65	240	35	25	. . .	75 HRB
430	Annealed bar	517	75	310	45	30	65	155
	Annealed and cold drawn	586	85	483	70	20	65	185
442	Annealed bar	515	75	310	45	30	50	160
	Annealed at 815 °C (1500 °F) and cold worked	545	79	427	62	35.5	79	92 HRC
446	Annealed bar	550	80	345	50	25	45	86 HRB
	Annealed at 815 °C (1500 °F) and cold drawn	607	88	462	67	26	64	96 HRB
Martensitic stainless steels(b)								
403	Annealed bar	515	75	275	40	35	70	82 HRB
	Tempered bar	765	111	585	85	23	67	97 HRB
410	Oil quenched from 980 °C (1800 °F); tempered at 540 °C (1000 °F); 16 mm (0.625 in.) bar	1085	158	1005	146	13	70	. . .
	Oil quenched from 980 °C (1800 °F); tempered at 40 °C (104 °F); 16 mm (0.625 in.) bar	1525	221	1225	178	15	64	45 HRB
414	Annealed bar	795	115	620	90	20	60	235
	Cold drawn bar	895	130	795	115	15	58	270
	Oil quenched from 980 °C (1800 °F); tempered at 650 °C (1200 °F)	1005	146	800	116	19	58	. . .
420	Annealed bar	655	95	345	50	25	55	195
	Annealed and cold drawn	760	110	690	100	14	40	228
431	Annealed bar	860	125	655	95	20	55	260
	Annealed and cold drawn	895	130	760	110	15	35	270
	Oil quenched from 980 °C (1800 °F); tempered at	831	121	738	107	20	64	. . .

	650 °C (1200 °F)							
	Oil quenched from 980 °C (1800 °F); tempered at 40 °C (104 °F)	1435	208	1140	166	17	59	45 HRC
440C	Annealed bar	760	110	450	65	14	25	97 HRB
	Annealed and cold drawn bar	860	125	690	100	7	20	260
	Hardened and tempered at 315 °C (600 °F)	1970	285	1900	275	2	10	580
Austenitic stainless steels[(b)]								
201	Annealed	760	110	380	55	52	. . .	87 HRB
	50% hard	1035	150	760	110	12	. . .	32 HRC
	Full hard	1275	185	965	140	8	. . .	41 HRC
	Extra hard	1550	225	1480	215	1	. . .	43 HRC
202	Annealed bar	515	75	275	40	40	. . .	. . .
	Annealed sheet	655	95	310	45	40	. . .	. . .
	50% hard sheet	1030	150	760	110	10	. . .	. . .
301	Annealed	725	105	275	40	60	70	. . .
	50% hard	1035	150	655	95	54	61	. . .
	Full hard	1415	205	1330	193	6	. . .	. . .
302	Annealed strip	620	90	275	40	55	. . .	80 HRB
	25% hard strip	860	125	515	75	12	. . .	25 HRC
	Annealed bar	585	85	240	35	60	70	80 HRB
303	Annealed bar	620	90	240	35	50	55	160
	Cold drawn	690	100	415	60	40	53	228

304	Annealed bar	585	85	235	34	60	70	149
	Annealed and cold drawn	690	100	415	60	45	. . .	212
	Cold-drawn high tensile	860	125	655	95	25	. . .	275
305	Annealed sheet	585	85	260	38	50	. . .	80 HRB
308	Annealed bar	585	85	205	30	55	65	150
309	Annealed bar	655	95	275	40	45	65	83 HRB
310	Annealed sheet	620	90	310	45	45	. . .	85 HRB
	Annealed bar	655	95	275	40	45	65	160
314	Annealed bar	689	100	345	50	45	60	180
316	Annealed sheet	580	84	290	42	50	. . .	79 HRB
	Annealed bar	550	80	240	35	60	70	149
	Annealed and cold-drawn bar	620	90	415	60	45	65	190
317	Annealed sheet	620	90	275	40	45	. . .	85 HRB
	Annealed bar	585	85	275	40	50	. . .	160
321	Annealed sheet	620	90	240	35	45	. . .	80 HRB
	Annealed bar	585	85	240	35	55	65	150
	Annealed and cold-drawn bar	655	95	415	60	40	60	185
330	Annealed sheet	550	80	260	38	40	. . .	. . .
	Annealed bar	585	85	290	42	45	. . .	80 HRB
347	Annealed sheet	655	95	275	40	45	. . .	85 HRB
	Annealed bar	620	90	240	35	50	65	160

	Annealed and cold drawn bar	690	100	450	65	40	60	212
384	Annealed wire 1040 °C (1900 °F)	515	75	240	35	55	72	70 HRB
Maraging steels[b]								
18Ni(250)	Annealed	965	140	655	95	17	75	30 HRC
	Aged bar 32 mm (1.25 in.)	1844	269	1784	259	11	56.5	51.8 HRC
	Aged sheet 6 mm (0.25 in.)	1874	272	1832	266	8	40.8	50.6 HRC
18Ni(300)	Annealed	1034	150	758	110	18	72	32 HRC
	Aged bar 32 mm (1.25 in.)	2041	296	2020	293	11.6	55.8	54.7 HRC
	Aged sheet 6 mm (0.25 in.)	2169	315	2135	310	7.7	35	55.1 HRC
18Ni(350)	Annealed	1140	165	827	120	18	70	35 HRC
	Aged bar 32 mm (1.25 in.)	2391	347	2348	341	7.6	33.8	58.4 HRC
	Aged sheet 6 mm (0.25 in.)	2451	356	2395	347	3	15.4	57.7 HRC

Source: Ref 1

(a) All values are estimated minimum values; type 1100 series steels are rated on the basis of 0.10% max Si or coarse-grain melting practice; the mechanical properties shown are expected minimums for the sizes ranging from 19 to 31.8 mm (0.75 to 1.25 in.).

(b) Most data are for 25 mm (1 in.) diam bar.

In the selection process, what is required for one application may be totally inappropriate for another application. For example, steel beams for a railway bridge require a totally different set of properties than the steel rails that are attached to the wooden ties on the bridge deck. In designing the bridge, the steel must have sufficient strength to withstand substantial applied loads. In fact, the designer will generally select a steel with higher strength than actually required. Also, the designer knows that the steel must have fracture toughness to resist the growth and propagation of cracks and must be capable of being welded so that structural members can be joined without sacrificing strength and toughness. The steel bridge must also be corrosion resistant. This can be provided by a protective layer of paint. If painting is not allowed, small amounts of certain alloying elements such as copper and chromium can be added to the steel to inhibit or reduce corrosion rates. Thus, the steel selected for the bridge would be a high-strength low-alloy (HSLA) structural steel such as ASTM A572, grade 50 or possibly a weathering steel such as ASTM A588. A typical HSLA steel has a ferrite-pearlite microstructure as seen in Fig. 1 and is microalloyed with vanadium and/or niobium for strengthening. (*Microalloying* is a term used to describe the process of using small additions of carbonitride forming elements--titanium, vanadium, and niobium--to strengthen steels by grain refinement and precipitation hardening.)

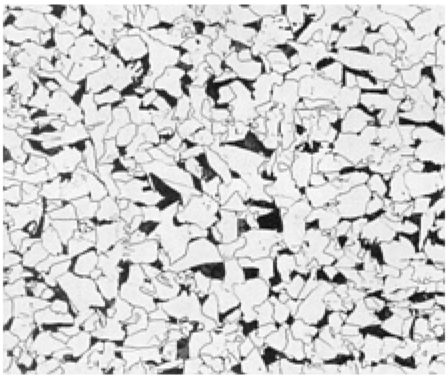

Fig. 1 Ferrite-pearlite microstructure of a typical HSLA structural steel (ASTM A 572, grade 50). 2% nital + 4% picral etch. 200×

On the other hand, the steel rails must have high strength coupled with excellent wear resistance. Modern rail steels consist of a fully pearlitic microstructure with a fine pearlite interlamellar spacing, as shown in Fig. 2. Pearlite is unique because it is a lamellar composite consisting of 88% soft, ductile ferrite and 12% hard, brittle cementite (Fe_3C). The hard cementite plates provide excellent wear resistance, especially when embedded in soft ferrite. Pearlitic steels have high strength and are fully adequate to support heavy axle loads of modern locomotives and freight cars. Most of the load is applied in compression. Pearlitic steels also have relatively poor toughness and cannot generally withstand impact loads without failure. The rail steel could not meet the requirements of the bridge builder, and the HSLA structural steel could not meet the requirements of the civil engineer who designed the bridge or the rail system.

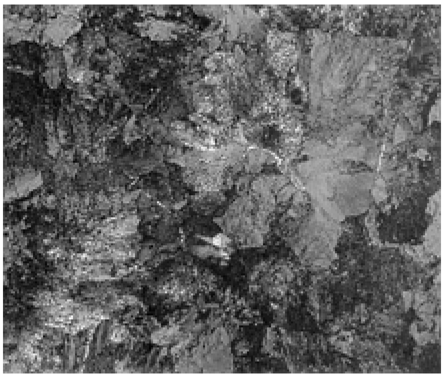

Fig. 2 Microstructure of a typical fully pearlitic rail steel showing the characteristic fine pearlite interlamellar spacing. 2% nital + 4% picral etch. 500×

A similar case can be made for the selection of cast irons. A cast machine housing on a large lathe requires a material with adequate strength, rigidity, and durability to support the applied load and a certain degree of damping capacity in order to rapidly attenuate (dampen) vibrations from the rotating parts of the lathe. The cast iron jaws of a crusher require a material with substantial wear resistance. For this application, a casting is required because wear-resistant steels are very difficult to machine. For the machine housing, gray cast iron is selected because it is relatively inexpensive, can be easily cast, and has the ability to dampen vibrations as a result of the graphite flakes present in its microstructure. These flakes are dispersed throughout the ferrite and pearlite matrix (Fig. 3). The graphite, being a major nonmetallic constituent in the gray iron, provides a tortuous path for sound to travel through the material. With so many flakes, sound waves are easily reflected and the sound dampened over a relatively short distance. However, for the jaw crusher, damping capacity is not a requirement. In this case, an alloy white cast iron is selected because of its high hardness and wear resistance. The white cast iron microstructure shown in Fig. 4 is graphite free and consists of martensite in a matrix of cementite. Both of these constituents are very hard and thus provide the required wear resistance. Thus, in this example the gray cast iron would not meet the requirements for the jaws of a crusher and the white cast iron would not meet the requirements for the lathe housing.

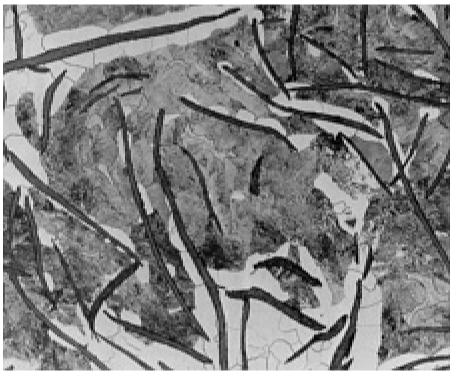

Fig. 3 Microstructure of a gray cast iron with a ferrite-pearlite matrix. Note the graphite flakes dispersed throughout the matrix. 4% picral etch. 320×. Courtesy of A.O. Benscoter, Lehigh University

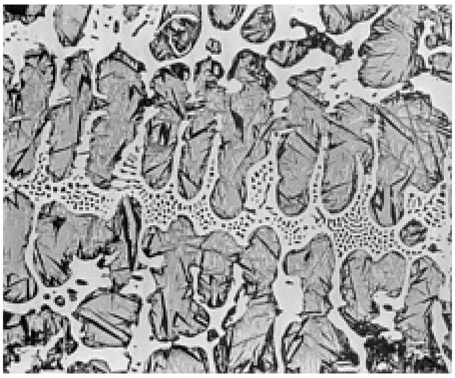

Fig. 4 Microstructure of an alloy white cast iron. White constituent is cementite and the darker constituent is martensite with some retained austenite. 4% picral etch. 250×. Courtesy of A.O. Benscoter, Lehigh University

Reference cited in this section

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Steelmaking Practices and Their Influence on Properties

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Introduction

THE MODERN PRACTICE of iron and steelmaking can be summarized by referring to the simplified flow diagrams shown in Fig. 1(a) and 1(b), which represent the sequence of steps for producing practically all steel products. Liquid iron, commonly referred to as pig iron, is produced in a blast furnace from iron ore, limestone, and coal (coke) (see Fig. 1(a)). Because it contains excessively high levels of silicon, manganese, carbon, and other elements, this liquid iron, together with scrap and fluxing agents, is then introduced into either a basic oxygen furnace or electric-arc furnace for further refining with oxygen that reduces the silicon, manganese, and carbon to acceptably low levels in the resulting steel. The steel is then tapped or poured into refractory-lined ladles. During this tapping operation, alloying elements that will determine the final chemistry of the steel are added to the ladle along with deoxidizing materials, which have a major influence on the final quality, formability, and cost. Following ladle treatment, which can also be supplemented by a remelting/refining step not indicated in Fig. 1(a), the steel is either cast into ingots or continuously cast. As shown on the lower right-hand portion of Fig. 1(a), ingots undergo a primary rolling step (ingot breakdown) before they are processed into semifinished shapes (blooms, billets, and slabs). Continuously cast steels require no primary rolling step. The semifinished products are then hot rolled. Some flat products are also cold rolled. Figure 1(b) presents the processes involved in converting the raw steel into the various mill-product forms.

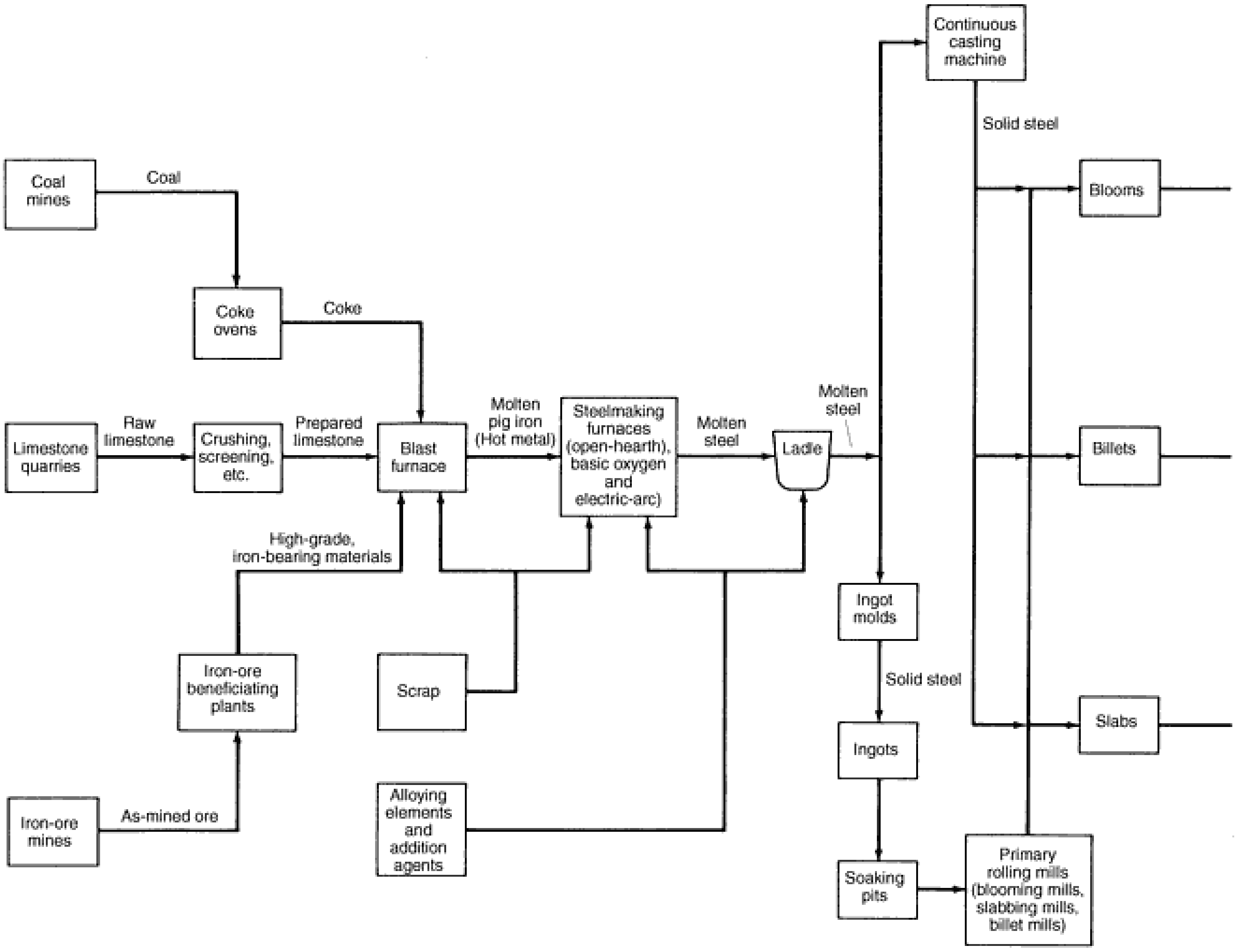
Continuous casting machine
Solid steel
Coal mines
Coal
Blooms
Coke ovens
Coke
Molten steel
Limestone quarries
Raw limestone
Crushing, screening, etc.
Prepared limestone
Blast furnace
Molten pig iron (Hot metal)
Steelmaking furnaces (open-hearth), basic oxygen and electric-arc)
Molten steel
Ladle
Billets
High-grade, iron-bearing materials
Ingot molds
Solid steel
Iron-ore beneficiating plants
Scrap
Slabs
Ingots
Iron-ore mines
As-mined ore
Alloying elements and addition agents
Soaking pits
Primary rolling mills (blooming mills, slabbing mills, billet mills)

Fig. 1(a) Flow diagram for blast furnace production of pig iron and steel

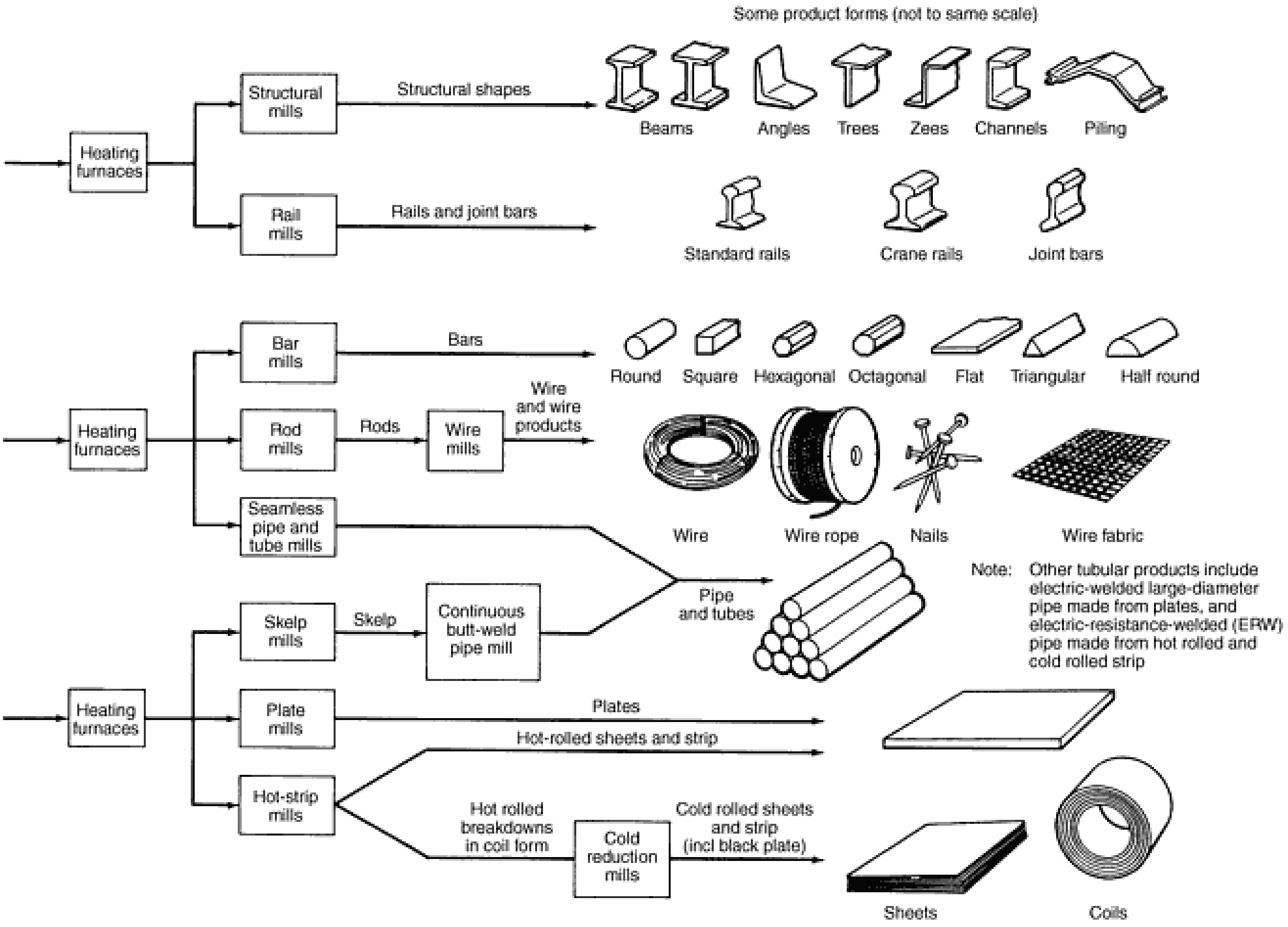
Some product forms (not to same scale)
Heating furnaces
Structural mills
Structural shapes
Beams
Angles
Trees
Zees
Channels
Piling
Rail mills
Rails and joint bars
Standard rails
Crane rails
Joint bars
Heating furnaces
Bar mills
Bars
Round
Square
Hexagonal
Octagonal
Flat
Triangular
Half round
Rod mills
Rods
Wire mills
Wire and wire products
Wire
Wire rope
Nails
Wire fabric
Seamless pipe and tube mills
Pipe and tubes
Note: Other tubular products include electric-welded large-diameter pipe made from plates, and electric-resistance-welded (ERW) pipe made from hot rolled and cold rolled strip
Heating furnaces
Skelp mills
Skelp
Continuous butt-weld pipe mill
Plate mills
Plates
Hot-rolled sheets and strip
Hot-strip mills
Hot rolled breakdowns in coil form
Cold reduction mills
Cold rolled sheets and strip (incl black plate)
Sheets
Coils

Fig. 1(b) Flow diagram showing the principal processes involved in converting raw steel into mill-product forms (excluding coated products)

Ironmaking

Physical Chemistry

Raw Materials. The modern practice of iron and steelmaking has evolved over seven centuries (Ref 1, 2, 3). The essential raw materials required for the present practice of pig iron production are iron ore, coal, limestone, and air. The important commercial forms of iron ore are hematite (Fe_2O_3), magnetite (Fe_3O_4), and limonite ($HFeO_2$), and concentrating steps. Iron ore is also used in the partially reduced and fluxed form of sinter as well as agglomerated forms of briquettes and pellets.

A good quality coal to produce coke is characterized by low contents of ash (<15%), inert material, and sulfur and high content of fixed carbon (Ref 4). Coal carbonization is carried out in coke ovens to produce metallurgical coke, which is the solid fuel burned in air inside the ironmaking reactor to produce the primary reductant of carbon monoxide gas. The reduction of iron oxide in the blast furnace also partially occurs directly by carbon in the coke.

Limestone ($CaCO_3$) and dolomite ($(Ca,Mg)CO_3$) are the common fluxes used in ironmaking. These carbonates are mostly calcined to affect the endothermic, pressure-sensitive decomposition reaction outside the blast furnace. The primary function of the flux is to combine with the gangue comprising silica and alumina in the ore, sulfur, and ash in the coke. Formation and separation of molten slag by this combination enables the production of liquid pig iron with controlled amounts of silicon, sulfur and manganese. The hot air used in the furnace at an average temperature of 1200 °C (2190 °F) and a pressurized flow rate of 70 m^3/s (150,000 scfm) provides oxygen for burning the coke, supports the counter-current flow of gases in the reactor, and partially meets the heat requirements of a typical furnace.

The furnace is lined with alumina-silica bricks, and the hearth is made of carbon blocks. As stated earlier the product of the blast furnace is a liquid pig iron, which is used to produce steel by further refining. Liquid slag also collects in the bottom of the blast furnace over the liquid metal pool in the hearth, and a by-product gas with useful calorific value is collected from the top. The productivity of a blast furnace is measured in terms of the production of hot metal or pig iron per day per unit inside volume of the reactor. Typical productivity of an efficient blast furnace is in the range of 2 to 3 metric tons/m^3 per day.

Chemical Reactions in the Blast Furnace. The preparation of the descending burden essentially determines temperature-dependent reducibility. The temperature profile must be such that only sufficient heat is available at the appropriate locations for reduction and melting in the furnace. Premature formation and melting of slag causes irregular burden descent. The consumption of coke and flux and the heat loss with the off gas are minimized in the modern blast furnaces to improve the productivity. It can be readily seen that lower coke and flux rates provide higher volumes for iron units in the furnace.

In the blast-furnace stack (Fig. 2) there is countercurrent flow of gas and solids. As oxygen is transferred from solids to gas, heat transfer occurs from gas to solid (Ref 5). Carbon dioxide gas (CO_2) is produced in front of the tuyeres where excess oxygen is available in the blast (reaction 1, Eq 1) but immediately converts to carbon monoxide (CO) by reaction 2 (Eq 2) due to thermodynamic equilibrium conditions. The temperature in front of the tuyeres, known as the raceway adiabatic flame temperature (RAFT), exceeds 2000 °C (3630 °F) when high exothermic heat is generated by carbon combustion. Principally, two types of gas-solid chemical reactions occur in the stack where coke is oxidized by CO_2 to produce CO gas and iron oxides are reduced by carbon monoxide in the presence of an excess carbon at a high temperature (Ref 6, 7, 8). These reactions are shown as follows:

$$C + O_2 \leftrightarrow CO_2 \qquad \textbf{(Eq 1)}$$

$$CO_2 + C \leftrightarrow 2CO \qquad \textbf{(Eq 2)}$$

$$3CO + Fe_2O_3 \leftrightarrow 2Fe + 3CO_2 \qquad \textbf{(Eq 3)}$$

Reaction 2 is also known as the "solution-loss" reaction as carbon is lost before it can reach the tuyeres. This endothermic reaction is promoted by increased temperature, decreased pressure, and a high ratio of CO_2 to CO. The reverse reaction catalyzed by iron or iron oxide occurs at lower temperatures causing deposition of carbon. The reduction of iron oxide by carbon monoxide can occur in three steps at temperatures over 600 °C (1110 °F), where Fe_2O_3 successively reduces to Fe_3O_4, FeO, and finally iron. In addition to reducing the oxides of iron, carbon monoxide reduces the oxides of manganese, silicon, and phosphorus present in the gangue of the ore and ash of the coke:

$$MnO + CO \leftrightarrow Mn + CO_2 \qquad \textbf{(Eq 4)}$$

$$SiO_2 + 2CO \leftrightarrow Si + 2CO_2 \qquad \textbf{(Eq 5)}$$

$$P_2O_5 + 5CO \leftrightarrow 2P + 5CO_2 \qquad \textbf{(Eq 6)}$$

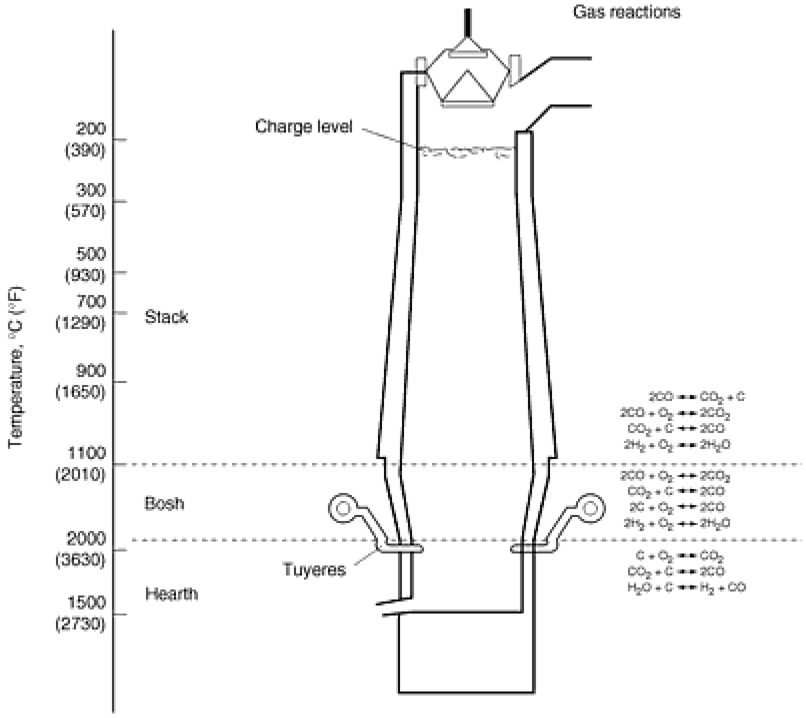

Fig. 2 Schematic diagram of a blast furnace showing the gas reactions as a function of temperature

The distribution of manganese, silicon, phosphorus, and sulfur in the metal and slag primarily depend on the temperature and composition (basicity) of the slag and the furnace oxygen potential at the hearth. The hot metal is usually saturated with carbon. Blast furnaces offer little in terms of lowering phosphorus in the metal, but conditions are suitable for sulfur control. Silicon and manganese levels in the hot metal are usually dictated by the steelmaking practice.

The water vapor in the hot blast also plays an important role in the reduction, as hydrogen gas is produced by the reduction of water by carbon. Hydrogen gas serves as an efficient reductant, particularly at lower temperatures in the furnace:

$$H_2O + C \leftrightarrow H_2 + CO \qquad \textbf{(Eq 7)}$$

$$FeO + H_2 \leftrightarrow Fe + H_2O \qquad \textbf{(Eq 8)}$$

It is the oxidation of carbon by the hot blast and some of the reduction reactions involving carbon monoxide that furnish the heat in the furnace to dry the charge, decompose the limestone, replace the heat losses, and provide the sensible heat of the hot metal, off gas, and slag.

Slag Chemistry. Slag is the fusible material formed by the chemical reaction of a flux with the gangue of an ore, with the ash from a fuel, or with the impurities oxidized during the refining of a metal. The compounds in a slag are formed by the neutralization reaction of basic and acidic oxides. In a blast furnace, the slag that forms first in the bosh zone (Fig. 2) is FeO-CaO-Al_2O_3-SiO_2 type if fluxed sinter is used in the burden. The actual composition depends on the amount of gangue materials in the ore and the degree of gaseous reduction in the furnace. As this slag comes in contact with the coke, FeO is reduced, and the slag changes to CaO-Al_2O_3-SiO_2-MgO type. The final slag in the hearth is formed when the coke ash is taken into solution. The composition of the final slag comprising CaO-Al_2O_3-SiO_2-MgO-CaS-MnO depends on the desired basicity and temperature of the slag, which in turn controls the partitioning of manganese, sulfur, and silicon in the hot metal. Typically, 40 wt% of silica and calcia are present with smaller quantities of magnesia, alumina, calcium sulfide, and manganese oxide. High-alumina refractory slags are undesirable, therefore, some removal of alumina is practiced during beneficiation of the iron ore.

There are two main considerations concerning the slag in the blast furnace. One is to have a slag that will be molten at the hearth temperatures and will not hinder the free descent of the burden in the furnace; the other is to control the composition of the iron from the furnace, particularly in respect to silicon and sulfur. Oxygen potential, temperature, and basicity are factors that determine the ability of the slag to control the hot metal sulfur, manganese, and silicon levels.

Physical Condition of the Reactor. The blast furnace may be structurally divided into three zones. The highest temperatures (>2000 °C, or 3630 °F) are attained in the hearth immediately in front of the tuyeres. Temperatures fall steeply (to 1600 °C, or 2910 °F) on the same horizontal plane closer to the furnace center line. The inverted, truncated-cone section is the bosh, and above this is the stack (see Fig. 2). Temperature falls uniformly to ~1100 °C (2010 °F) at the top of the bosh and to ~800 °C (1470 °F) midway up the stack. A temperature of ~250 °C (480 °F) is attained at the top of the furnace. The oxygen in the air blast is entirely consumed by reaction with the coke charge within a small radius of the tuyeres outside which CO_2 reacts with more coke to form carbon monoxide. At temperatures >1000 °C (1830 °F), the concentration of CO_2 is negligible and the total pressure of carbonaceous gases is equal to the partial pressure of carbon monoxide. Between the temperatures of 400 and 1000 °C (750 and 1830 °F), the partial pressures of both the gases are significant. The total gas pressure is usually close to atmospheric at the top of the stack and between 1.3 to 1.5 atm at the tuyere level consisting of ~60 vol% of N_2. The temperature conditions and the CO-CO_2 balance determines the oxygen potential at any location within the blast furnace. The ability and rate of the furnace to reduce the iron ore depends on the temperature, diffusion of oxygen, amount of volume change upon reduction, availability of hydrogen, onset of slag formation, reduction with solid carbon, presence of gangue, and the use of prereduced sinter material. The top gas analysis in terms of CO/CO_2 ratio is a good indicator of blast furnace performance in addition to the temperature and compositions of the hot metal and slag produced.

Composition of Pig Iron

Charge Balance. The primary impurities in molten pig iron or hot metal are carbon, sulfur, manganese, silicon, and phosphorus. While manganese, silicon, and phosphorus are present in the ore as oxides, carbon and sulfur are in the coke of the burden. Silica is also present in the ash of the coke. A typical hot metal has 1.0 to 2.0% Si (determined by the blast furnace operating conditions, slag chemistry, and the steelmaking heat requirements), 0.1 to 0.5% P, 0.04 to 0.07% S, 0.75 to 1.25% Mn, and up to 4.5% C. Carbon is usually dissolved in molten iron close to the solubility limit at the temperature. Carbon is insoluble in slag. Phosphorus oxide is reduced, and phosphorus is dissolved in molten iron. Blast furnace slags are not suitable for removing phosphorus. Sulfur is mostly transferred to the slag as calcium sulfide. A reducing furnace condition, high temperature, and high slag basicity (CaO/SiO_2) are conditions that favor sulfur transfer to the slag (Ref 9). Therefore, good desulfurization cannot be achieved during steelmaking as the conditions are highly oxidizing (see the section on steelmaking).

Oxygen potential in the system affects the distribution of all the elements that partition themselves between the metal and the slag. Oxygen potentials favorable for sulfur control in hot metal are unsuitable for silicon and manganese removal. For a given carbon activity and carbon monoxide partial pressure in the hearth zone, an increase in temperature helps increase the partitioning of manganese, silicon, and sulfur. The activity of various oxides in the slag and the activity coefficient of different solutes in molten iron are important factors in determining the distribution of impurities in pig iron. Empirical relationships have been established between the slag composition and the activity of oxide components (Ref 10, 11, 12, 13) as well as the sulfide capacity of the slag (Ref 14). An increase in lime and magnesia content of slag increases the sulfide capacity. Higher partitioning of sulfur in the blast furnace is also encouraged by a higher carbon activity in the hot metal. If a low-silicon, low-sulfur hot metal is desired, a pretreatment of hot metal becomes necessary prior to steelmaking (see the section "Hot Metal Pretreatment"). Use of a low-ash, low-sulfur coke is also desired for making low-sulfur pig iron. Other important solutes that partition between the slag and metal are chromium and titanium. These metals are present as oxides in some ore bodies used for ironmaking. Normally ~50 to 60% of the chromium is reduced into the hot metal. Titanium oxide is reduced to titanium carbide and carbonitrides. Sometimes titania-bearing ore is charged in the furnace to protect the hearth from eroding by making the slag and metal viscous.

Advances in Blast Furnace Technology

Significant improvements have been made over the last forty years in blast furnace productivity in terms of hot metal produced per unit volume of the furnace and the amount of fuel used. These improvements are the result of several advancements. Use of high-strength, super-fluxed sinters permitting the use of higher flame temperatures, coal washing, and blending to lower ash and sulfur; stamp (compression) charging for carbonization and uniform sizing of coke for higher coke strength and furnace permeability; and charging sequence optimization for proper distribution of burden using movable throat armors are some of the developments in charged material management.

High hot-blast temperatures of 1250 °C (2280 °F) are now commonly used in several blast furnaces around the world, which has a direct bearing on the coke rate of the furnace. The ability to use high blast temperatures and the need to control the flame temperature has allowed the use of hydrocarbon fuel injection. This development enhances the reducing power of the bosh gas and in turn lowers the coke rate. Natural gas, coke-oven gas, oil, tar and pulverized coal, or oil-coal slurry have all been effectively used as a fuel supplement to the blast furnace. The discovery of methods to control the flame temperature also allows the enrichment of blast air with oxygen. A 1% increase of oxygen typically improves the furnace productivity by 2 to 4% depending on the burden reducibility.

High top-pressure capability has allowed the use of higher wind rates to the furnace without causing burden lifting. There is a corresponding increase in the production rate when the gas inside the furnace is compressed. Approximately 205 MPa (30 psi) top pressures have been successfully used. The development has also necessitated improvements in the off-gas handling system.

Hot Metal Pretreatment

The blast furnace does not always produce a molten metal with desired compositional levels of sulfur, silicon, and phosphorus due to the fact that process conditions required for desirable partitioning of these elements between the slag and the metal are often conflicting. Higher levels of these solutes may be present in the hot metal due to higher gangue in the ore and/or high sulfur in the coke. Therefore, a pretreatment of the hot metal is carried out before the hot metal can be used for steelmaking. Pretreatment may be carried out at the blast furnace runner, hot-metal ladle, or the mixer because temperature of the metal is different at these three stages. The blast furnace runner also allows a large reaction area between the reagents and the hot metal. The silicon, sulfur, and phosphorus can be lowered by a basic refractory lining of the mixer and by forming a lime-rich oxide slag. An active mixer practice could thus be used by feeding a combined source of iron oxide and lime to the melt in the mixer, such as a fluxed sinter, a mixture of lime and mill scale, or lime and iron-ore fines.

Ladle desulfurization has become an important process step due to the demand for ultralow sulfur steels. Soda ash, calcium oxide, calcium carbide, or a mixture of these, is injected with air through a lance immersed in hot-metal ladles. Calcium serves as the desulfurizing agent producing calcium sulfide. Sulfur levels of 0.015 and 0.008% have been reported using lime or calcium carbide as the reagents, respectively (Ref 15). Use of lime-soda ash mixtures is the most economic method where the kinetics of desulfurization can be enhanced mechanically.

Alternative Sources of Iron

Direct-Reduced Iron. The need to employ low-grade ores and types of fuel unsuitable for blast furnaces has been driving the search for alternative sources of iron. Processes that produce iron by reduction of iron ore below the melting point of the iron produced are generally classified as direct-reduction processes and the products are known as direct-reduced iron (DRI) or sponge iron. The processes that produce molten iron, similar to blast furnace hot metal, are classified as smelting-reduction processes. These processes usually split the solid-state reduction steps and the liquid melting and slagging steps into two separate reactors eliminating the need for high-strength prepared burden. Direct-reduced iron contributes 5 to 6% of the world's total ironmaking capacity with ~34 million metric tonnes of DRI produced annually in 1996. Direct-reduced iron is mostly used as a substitute for scrap in steelmaking. Availability of low-cost scrap and the high cost of electricity are deterrents for the use of DRI in industrialized nations, whereas countries endowed with inexpensive natural gas, non-coking coals, hydroelectric power, and access to suitable ore reserves prefer this alternative route to making iron.

Chemical reactions for making DRI are similar to those in the blast furnaces. When reduction is carried out below ~1000 °C (1830 °F) and H_2 gases are primary reductants (generated externally) and the product is porous. Metallic iron also absorbs some carbon to produce 1 to 2.5% iron carbide as cementite when gaseous reduction is carried out. When pure carbon monoxide is used to reduce dense Fe_2O_3, the reduction stops at ~40% at 700 °C (1290 °F) and at ~85% at 800 °C (1470 °F), but is completed at higher temperatures (Ref 16). Above 1000 °C (1830 °F), carbon reacts with moisture and CO_2 gas producing carbon monoxide and H_2, thus renewing the reduction potential of the gas. Processes that produce DRI directly from solid coal without prior gasification of its fixed carbon use temperatures in excess of 1000 °C (1830 °F). In the case of iron oxide reduction with coal, the reactions between carbon and iron oxide particles begin only at the points of contact, but are disrupted once metallic iron is formed in the intermediate phase. Thereafter, the reduction can proceed only as a result of the diffusion of carbon atoms through the metallic iron layer to the residual oxide. Thus, in direct-reduction processes based on either solid or liquid reductants, it is essential to convert the reductant to a reducing gas.

A temperature of 1200 °C (2190 °F) is considered the upper limit for the direct-reduction processes, above which the metallic iron formed absorbs carbon resulting in fusing and melting of the solid. The direct-smelting processes thus operate with product temperatures >1300 °C (2370 °F), because carbon is absorbed rapidly and a liquid hot metal forms. Table 1 lists the gas-based and coal-based direct-reduction processes as well as the electricity and fuel-based, smelting-reduction processes. A complete description of all these recent developments can be found in Ref 17.

Table 1 Classification of available direct-reduction and smelting-reduction processes

Direct-reduction processes--reducing gas generated externally from reduction furnace **Shaft-furnace processes, moving-bed** Wiberg-Soderfors Midrex HYL III Armco NSC Purofer **Shaft-furnace processes, static-bed** HYL I and II **Fluidized-bed processes** FIOR HIB
Direct-smelting processes Electric-furnace smelting processes Pig iron electric furnace DLM Oxyfuel smelting systems INRED KR Kawasaki CGS
Direct-reduction processes--reducing gas generated from hydrocarbons in reduction furnace Kiln processes Krup-Renn Krupp-CODIR SL/RN ACCAR DRC

    - LS-RIOR
- Rotary-hearth processes
    - INMETCO
    - Salem
- Retort processes
    - Hogänäs
    - Kinglor-Metor
- Shaft-furnace process, moving-bed
    - Midrex Electrothermal

Plasma processes

- Nontransferred arc
    - Plasmasmelt
    - Plasmared
- Transferred arc
    - ELRED
    - EPP
    - SSP
    - The Toronto system
    - Falling film plasma reactor

Source: Ref 17

The effectiveness of a direct-reduction process is measured through several indices. Percent total iron and percent metallic iron (including cementite) lead to the commercially used index of degree of metallization, which is the percent ratio of total weight of metallic iron to the total weight of iron in the product. The degree of metallization normally ranges between 90 and 95% depending on the reducibility of the original iron oxide and the process chosen. Percent reduction is a measure of the amount of oxygen removed during reduction. The amount of gangue in DRI, the level of sulfur (particularly for coal-based DRI), and the amount of fines affect the productivity of the steelmaking reactor where DRI is used.

Both moving- and static-bed shaft furnaces, as well as fluidized-bed processes, are used for making DRI using externally generated reducing gases. Usually a kiln-type furnace, a rotary hearth, or a retort furnace is used when coal is directly used as the fuel in DRI manufacturing. In all coal-based direct-reduction processes, sized ore and a coarse fraction of noncoking coal are fed into the rotary kiln from the inlet end in the required proportions. The growth of gas-based, direct-reduction processes is more favorable than the coal-based methods due to easier process control, higher availability of reactor, better energy efficiency, lower sulfur, and higher carbon in the product. In addition, the productivity of a rotary kiln is between 0.3 to 0.5 metric tons/m^3 per day compared with over 2 metric tons/m^3 per day for a natural gas-based process.

Smelting-reduction processes that produce molten iron use low-shaft electric furnaces. A burden of agglomerated or lump ore, coal, or coke and limestone are directly charged into the furnace. The submerged-arc concept is used with Soderberg self-baking carbon electrodes. As an alternative to the electric-arc furnace, oxyfuel smelting systems are also used for smelting reduction. Flash smelting of the concentrate by coal and oxygen is accomplished in the first stage where close to 90% of the process energy is supplied. In the first stage, the ore is prereduced to FeO. In the second stage, the prereduced and heated material is further reduced mainly by direct reduction with carbon and then smelted. The COREX (or KR) process for smelting reduction conducts the blast furnace functions of preheating and gaseous reduction and smelting in two separate reactors (Fig. 3). Essentially, the process comprises a two-stage operation in which DRI from a shaft furnace is charged without cooling into a connected melter gasifier operating at 3 to 5 atm of pressure.

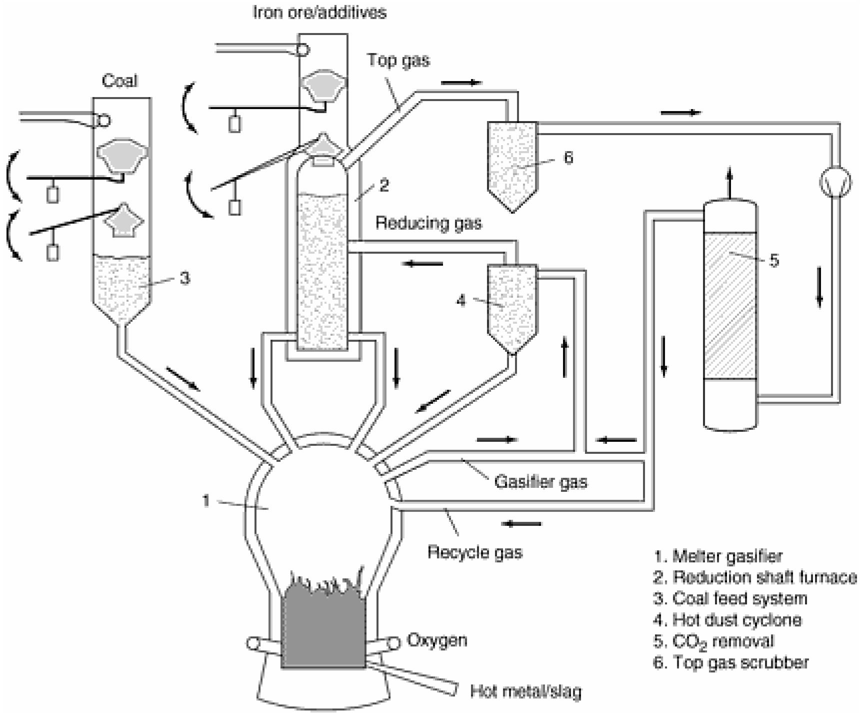

Fig. 3 Schematic diagram of the COREX smelting-reduction process

Several plasma-arc reduction processes have also been developed to produce molten iron directly from unprepared burden. There are many processes for smelting reduction presently being developed through different stages of commercialization. Several of these rely on the recovery of calorific value of the exhaust process gas to make the technology viable. Although coking is not necessary, some processes are restricted by the ash and volatile contents of coal that can be used. Smelting-reduction processes have significant potential for the production of ferroalloys.

Iron Carbide. A promising alternative source of iron has been found in iron carbide, which is produced by the reduction of iron ore fines by hydrogen gas and subsequent carburization by carbon monoxide gas in a fluidized-bed reactor. The process produces iron carbide powder, which is hard, nonfriable, resistant to oxidation, and has the potential to replace DRI, scrap, or molten iron to produce steel at a lower cost. The process typically operates at a temperature of 600 °C (1110 °F) and pressure of 1.8 atm, producing a 7% C 93% Fe material. The reactions for the production of iron carbide from hematite or magnetite fine ore are:

$$3Fe_2O_3 + 11H_2 + 2CO \leftrightarrow 2Fe_3C + 11H_2O \quad \textbf{(Eq 9)}$$

$$Fe_3O_4 + 5H_2 + CO \leftrightarrow Fe_3C + 5H_2O \quad \textbf{(Eq 10)}$$

The combined carbon in iron carbide forms a latent source of energy to the extent that a 1200 °C (2190 °F) preheated iron carbide can constitute 100% of the charge in oxygen steelmaking (Ref 18). Capital cost per annual ton of iron is about one-third that of blast-furnace, coke oven combinations and about one-half that of current DRI plants. Quality steel can be produced because iron carbide does not contain tramp elements and has no sulfur. Equations 9 and 10 indicate that water is the only by-product in iron carbide production.

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Steelmaking

In the previous section it was shown that the end product of ironmaking is molten iron produced through large capacity blast furnaces or sponge iron produced through smaller capacity direct- or indirect-reduction processes. Liquid steel is produced as the end product of steelmaking, which is subsequently cast as an ingot or continuously cast. The smelting-reduction or direct steelmaking processes under development will eliminate this sharp distinction, if successfully developed. Steelmaking can be broadly classified into two steps: primary steelmaking in a converter or furnace and secondary steelmaking in a ladle. Ordinary grades of steel may bypass the secondary steelmaking processes. The two most important steelmaking processes are the electric-arc furnace (EAF) process and the basic oxygen furnace (BOF) process or LD (Linz-Donawitz) process. The EAF process accounts for 35 to 40% of the world steel production and BOF produces 55 to 60% of steel. Some other processes, such as the open-hearth furnace, are still practiced in a few countries to produce special steels.

Basic Oxygen Steelmaking (Ref 19)

Charge Constituents. Oxygen steelmaking uses gaseous oxygen as the primary agent for autothermic generation of heat as a result of the oxidation of dissolved impurities present in hot metal and scrap, such as carbon, silicon, manganese, sulfur and phosphorus, and to some extent, by oxidation of iron. Top blowing is the most common form of oxygen steelmaking, but bottom as well as combined blowing are process variations that are also practiced. In the top-blowing process, oxygen is blown at supersonic velocity with the help of a water-cooled lance inserted through the mouth of the vessel. The vessel is lined with basic refractories like tar-bonded dolomite or carbon magnesite. The charge consists of steel scrap, hot metal, and flux--all charged through the mouth of the converter. While scrap is added as the source of iron units as well as a coolant, iron ore also provides a source of oxygen and is sometimes charged in the vessel. Lime is the primary flux for making slag but fluorspar and silica can also be added depending on the slag requirements. Typically 10 to 30% of the metallic charge is scrap, which helps control the heat generated by the exothermic oxidation reactions. The flux requirement and the slag volume produced strongly depends on the hot metal composition.

Process Description. Figure 4 shows a schematic diagram of a BOF. The converter is tilted approximately 30 to 40°, and the scrap is charged into the vessel using charging buckets. Scrap is usually screened and presorted for compositional consistency. Hot metal is then poured on the scrap. The vessel is then tilted back to an upright position for blowing oxygen. An oxygen lance is gradually lowered to a specified distance from the bath surface, and oxygen is started simultaneously. Within the first five minutes, all the lime is added through mechanized hoppers to flux the oxides of silicon, manganese, and iron. The limesilicate slag formed essentially contains CaO, SiO_2, FeO, MnO, and P_2O_5. After specified periods the lance is gradually lowered to the lowest position where carbon is oxidized to carbon monoxide and carbon dioxide. Only ~10% CO_2 is present in the top waste gas, which is collected through hoods placed on top of the vessel mouth during blowing. Total blowing time varies between 17 and 22 min, depending on the impurity content and the lance design. The lance is raised at the end of the blow. Steel is tapped into a ladle between 1650 and 1700 °C (3000 and 3090 °F) and the slag is removed by tilting the converter. Refractories require a preheat only when cold started for the first heat. Subsequent heats are produced on a continuous basis until the vessel is ready for a change of the refractory lining.

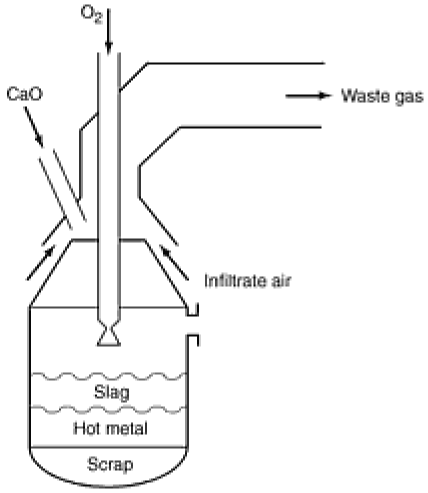

Fig. 4 Schematic diagram of the basic oxygen furnace

The typical end-point composition of steel is 0.04-0.06 wt% C, termed "turn-down" carbon; 0.2 wt% Mn, and 0.02 wt% P and S, depending on the composition of the charge materials used. The generation of metal droplets due to the impact of the jet on the metal surface and the evolution of metal and slag composition during the progress of a blow, as well as the kinetics of gas-metal-slag interactions, are important process characteristics which determine the efficiency of the converter. The important gas-metal and gas-slag reactions during steelmaking are:

- Oxidation of dissolved impurities in iron such as carbon, silicon, manganese, and phosphorus by gaseous oxygen
- Reduction of FeO and MnO in the slag by rising CO/CO_2 gas bubbles
- Dissolution of gases such as hydrogen and nitrogen in liquid steel

Figure 5 shows the evolution of bath composition and slag composition in a BOF converter. This figure shows that silicon is oxidized first within the first 3 to 4 min of the blow. However, transfer of sulfur, phosphorus, manganese, and carbon occurs over the entire blow period. As the blow progresses, lime (CaO) gradually dissolves in the slag, and the mass of slag increases over blowing time due to lime and iron oxide dissolution. The temperature of the liquid metal gradually increases from an initial 1250 to 1400 °C (2280 to 2550 °F) to ~1600 to 1700 °C (2910 to 3090 °F) at the end of the blow.

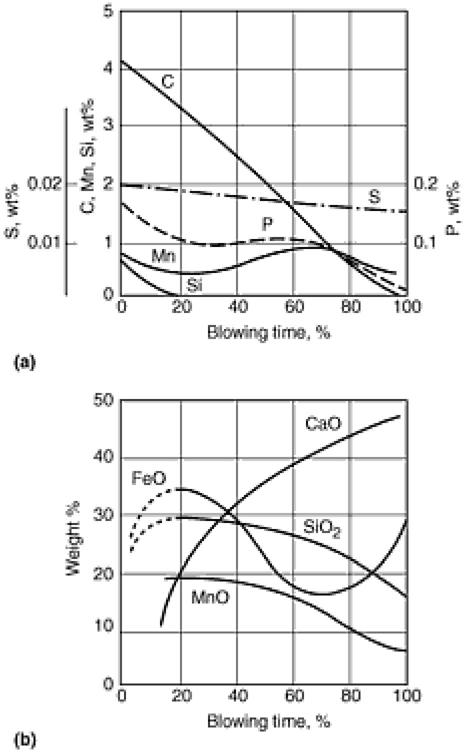

Fig. 5 Composition of (a) steel bath and (b) slag in a basic oxygen furnace converter as a function of blowing time

At the beginning of the blow, the distance of the lance tip from the bath surface is kept high, and after the formation of an initial slag rich in FeO and SiO_2, the lance is lowered. The slag starts to foam by around one-third of the blow, and the FeO content of the slag begins to decrease. Beyond three-quarters of the blow, the decarburization rate falls and the FeO content of the slag continuously increases to accommodate most of the oxygen that is not used for carbon oxidation. Toward the end of the blow, the rate of increase of FeO in the slag depends primarily on the lance height and the carbon content of the metal and on the amount of undissolved lime and viscosity of the slag. It can be readily seen that a high level of FeO in the slag directly affects the converter productivity. The equilibrium oxygen activity in liquid steel at tapping temperatures is a function of the turn-down carbon content (Ref 20).

At the end of the blow and after the lance is withdrawn, a temperature measurement is taken with an immersion thermocouple and a chemical analysis is done on the bath sample within five minutes. If the bath is too hot, ore or limestone is added as a coolant. A short-period reblow may be necessary if the temperature is too low. Temperature in the BOF is controlled by using a thermally balanced charge of hot metal and scrap such that composition and temperature are achieved at turn down, as desired. The BOF end points are completely computer controlled.

Process Capabilities. The basic oxygen process is characterized by (1) use of gaseous oxygen as the sole refining agent, (2) a charge largely composed of molten-blast furnace iron, and (3) rapid chemical reactions in a low surface-to-volume bath, minimizing external heat losses. Basic oxygen furnace steelmaking is an autothermal process, which relies on the oxidation of impurities in hot metal, therefore, a certain amount of hot charge is essential. Important attributes of a tapped steel product are the levels of carbon, oxygen, and other gaseous impurities, as well as the temperature, which affect secondary steelmaking. Control of oxygen and carbon are related to the loss of iron as FeO in the slag, which is undesirable. High levels of silicon in the hot metal require higher amounts of lime for fluxing and lower the converter productivity because larger volume of the converter is occupied by the slag. On the other hand, if low-silicon hot metal is refined, addition of sand can be necessary to create the required volume of slag for refining reactions. Control of sulfur and phosphorus are important for steel properties. Thus, the capabilities of a BOF reactor in terms of productivity are limited by the hot metal composition, scrap rate, desired carbon level, and the finishing temperature.

Electric-Arc Steelmaking (Ref 21)

Furnace Description. The classical blast furnace/BOF integrated steel plants are giving way to modern establishments of EAF/continuous-caster minimill steel production route. For steelmaking purposes, three-phase, alternating current (ac) direct-arc and direct current (dc) direct-arc furnaces, as well as induction furnaces are commonly used. In three-phase, ac direct-arc processes, current is passed from one electrode down through an arc and the metal charge, then from the charge up through an arc to another electrode. In the dc direct-arc furnaces, current passes from one electrode through an arc and the metal charge to an electrode in the bottom of the furnace. Current is induced in the steel by an oscillating magnetic field in low-, medium-, or high-frequency induction furnaces. Indirect-arc furnaces use radiation heating to heat the charge where the arc is directly struck between the two electrodes. These furnaces are not common for steelmaking. Presently, high-alloy, stainless, bearing, and other high-quality steels as well as low-alloy and plain-carbon steels are produced in EAFs.

Figure 6 shows a schematic cross section of an EAF. Commercial EAFs are almost exclusively lined with basic refractories of burned magnesite or direct-bonded, chrome-magnesite bricks with roofs made of high alumina-bricks. All the ingot cast, continuous cast, and most of the foundry-grade steels are produced in basic-lined furnaces, which can melt highly alloyed steel scrap as well as plain-carbon scrap. Basic furnaces can produce steel from a wide range of scrap compositions with the added advantage of refining high-sulfur and high-phosphorus melts. The time required for working the heat due to faster oxidation and the loss of iron in the slag due to lower slag volume are lower in the acid process, which uses a siliceous slag.

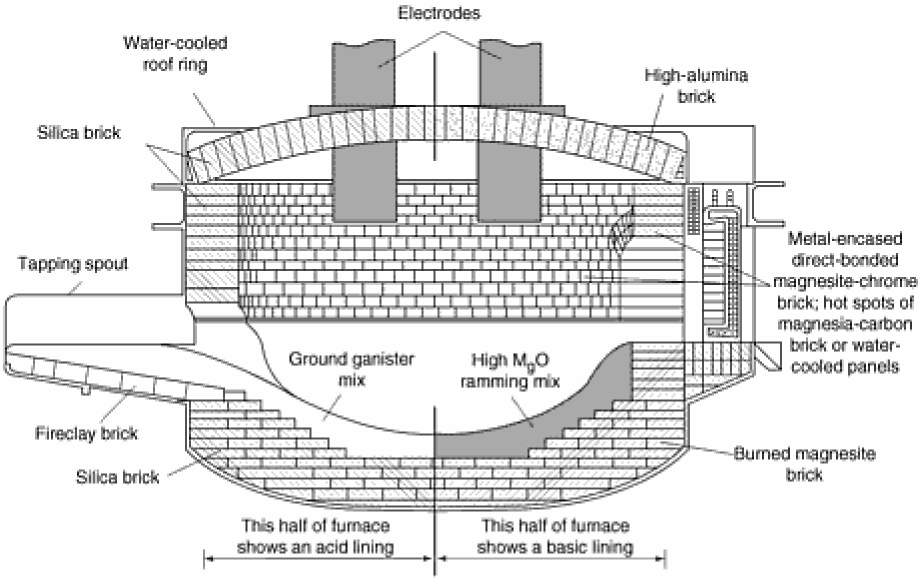
Electrodes
Water-cooled roof ring
High-alumina brick
Silica brick
Metal-encased direct-bonded magnesite-chrome brick; hot spots of magnesia-carbon brick or water-cooled panels
Tapping spout
Ground ganister mix
High MgO ramming mix
Fireclay brick
Silica brick
Burned magnesite brick
This half of furnace shows an acid lining
This half of furnace shows a basic lining

Fig. 6 Schematic cross section of a typical electric-arc furnace showing the application of different refractories

Burden Preparation. Segregation of scrap is an important function in burden preparation for electric furnaces. Grade-wise separation of scrap is done (1) to conserve the valuable alloy content of steel scrap, (2) to use virgin alloys economically, and (3) to ensure that only the desired alloying elements end up in the finished steel product. The segregation is usually done online by spark testing along with accurate chemical analysis using spectrography. Separation of scrap on the basis of size and bulk density is also performed to blend the charge properly. Exclusive use of light scrap (bundles, turnings, punchings, etc.) lowers the productivity by occupying a large volume in the furnace. Light scrap is also prone to oxidation. Light scrap as the initial charge can damage the hearth as the arc can bore through the metallic charge. A charge comprising all heavy scrap (ingots, butts, crops, etc.) is also not suitable as the roof and walls of the furnace are not shielded causing refractory damage. Essentially, the scrap charge is mixed for optimum melting, power utilization, and electrode consumption at minimum operating costs.

Direct-reduced iron can be used to partially or fully replace the scrap in an electric furnace charge. Often, DRI is preferred because it has a known uniform composition and contains no residual elements, such as copper, nickel, tin, or chromium. Direct-reduced iron also helps in the formation of a foamy slag due to the presence of carbon and iron oxide. Usually a 30% DRI and 70% scrap charge mix is used depending on the price of the two materials.

Charging Sequence. Electric-arc furnaces have removable roofs so scrap can be quickly and easily charged into the furnaces. The scrap is charged into the furnace using drop-bottom buckets. Large heavy scrap charges are loaded using magnets and placed slowly on the furnace bottom. Alloying materials which are difficult to oxidize, for example, copper, nickel, and molybdenum, can be charged prior to the melt down. Excess carbon is desired in the bath for meltdown, which is accomplished by oxygen injection or ore addition. If the carbon is low in the metallic charge, coke or scrap electrodes are used as recarburizers to allow ~0.20% higher carbon in the bath at melt down than is required in the finished steel. Oxygen injection is preferred for decarburization rather than mill scale or ore addition. If DRI is used as the metallic charge, it is added over the entire melt-down period through an opening in the furnace roof. Flux is added along with the metallic charge and placed away from the pitch of the electrodes as it is non-conducting.

Process Description. The process of making steel in the basic-lined EAF can be divided into (1) the melt-down period, (2) the oxidizing period, (3) the composition and temperature adjustment period, and (4) the tapping period.

Once the charging is complete, the electrodes are lowered to about an inch above the charge material and arcs are struck. Power and electrode consumption are highest during the melt-down period. Melting occurs by direct arcing as well as through radiation from the molten pool of metal collecting in the hearth. Burned or calcined lime as the flux is added toward the end of the melting of the first load of scrap charge.

The oxidizing period begins from the time the molten metal forms until the entire charge is in solution. During this period, phosphorus, silicon, manganese, carbon, and iron are oxidized. The sources of oxygen are the injected oxygen, furnace atmosphere, oxides of added alloying elements, and the ore, cinder, and mill scale added to the charge. The oxidizers are added in a controlled fashion to prevent excessive formation of carbon monoxide, which forces the slag to foam and spill out of the furnace. The bubbling action caused by carbon monoxide, called "carbon-boil," stirs the bath and makes it uniform in temperature and composition. Hydrogen and nitrogen are also lowered in the bath during carbon boil. Because electric-furnace steelmaking is not autothermal, that is, it relies on energy from the electric power used, the bath can be made hotter than a BOF. Thus, phosphorus reversal can occur if the slag is not highly basic.

Most carbon and low-alloy steel grades are made with a single-slag practice. The steel is finished by adjusting the composition and temperature to the desired value followed by tapping. The oxidizing period overlaps the adjustment period, and further lowering of sulfur and oxygen, if desired, is carried out in the ladles through secondary steelmaking.

In the double-slag practice to make high-quality carbon and alloy steels, the first oxidizing slag is removed from the furnace, and a reducing slag is prepared using burned lime, fluorspar, coke, and sand on top of the molten bath. Calcium carbide formed in the slags helps in desulfurization (see the section "Hot Metal Pretreatment"); however, ladle treatment to lower sulfur is now preferred. The composition is controlled by the slag chemistry as in the BOF. A typical melt-down slag comprises 41% lime, 14% each of iron oxide and silica, 9% magnesia, 4% alumina, and 13% manganous oxide, besides small quantities of phosphorus oxide and sulfur.

The electrodes are raised to allow tilting of the furnace for tapping. Stream oxidation is prevented during tapping of steel into ladles. Slag is removed from the furnace before, during, or after steel tapping depending on the practice used. A "wet-heel" practice is often used where a small amount of liquid steel is left behind in the furnace for the next heat. This helps in lowering the slag carry-over to the ladle. Sophisticated slide-gate arrangements are used to prevent slag carryover.

The main advantage of the arc furnace lies in flexibility in accepting charge materials in any proportion, that is, scrap, molten iron, prereduced material, and pellets, although industrial practice is mostly restricted to scrap and DRI. The control of electric power can be well regulated to impart heat to the bath at different desired rates. This allows a precise control of refining reactions. Oxygen can be blown to speed up the melt-down refining processes. The EAF offers a wide range of possibilities in controlled production of ordinary as well as high-quality special steels. Alloy steels can be made directly with secondary treatments. The process is best suited for the production of higher alloy steel grades, such as tool steels and stainless steels, because of the inherent advantage of process control. Small-capacity EAF can be put into service, whereas small oxygen furnaces are usually uneconomical. Because EAF is primarily scrap based, and the impurity control in scrap is of utmost importance, elements like copper and nickel are hard to remove under the steelmaking conditions.

Advances in Steelmaking Technology

Oxygen Bottom-Blowing Process. The essential difference from the oxygen top-blowing process, or BOF, is that all of the required oxygen gas is introduced through the bottom of the vessel with the help of tuyeres (Fig. 7). Lime can be injected in fine powder form along with oxygen to enhance the rate of dissolution of lime and the formation of a well-mixed homogeneous slag. The oxygen bottom-blowing process is also known as OBM, Q-BOP, or the LWS process depending on the type of tuyere design used for injecting oxygen. Natural gas or oil is used to shroud and protect the tuyeres from the intense heat of oxidation at the tip. The noise generated in bottom-blown processes as well as the turbulence in the bath are low compared with top-blown converters. Because bottom-blown processes operate more closely to the equilibrium conditions, the oxidation potential is much lower than top-blowing processes. This control of slag-metal equilibrium allows lower iron losses as FeO to the slag, higher manganese recoveries, less splashing (slopping) of the furnace, faster blow times, improved phosphorus and sulfur control, and lower dissolved oxygen and nitrogen contents. Bottom-blown converters have about ~2.0% higher yield. Easier process control is available in a Q-BOP as variability due to lance practice does not exist. Also, scrap rate in a bottom-blown process is lower along with a 10% lower oxygen rate than a top-blown process.

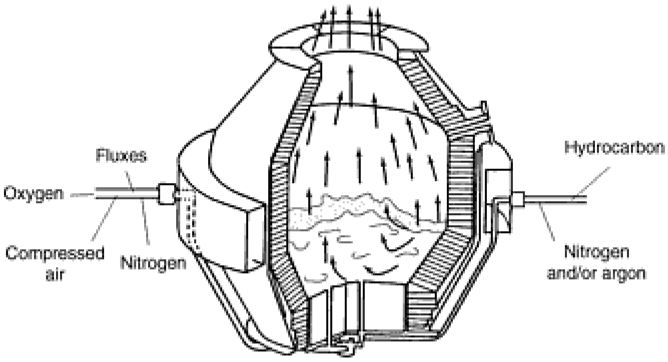

Fig. 7 Schematic representation of a bottom-blowing process

In general, less heat is produced in the bottom-blown oxygen steelmaking because less iron and manganese are oxidized for the same turn-down carbon level. Conversion of carbon to carbon dioxide is lower in bottom-blown converters and some of the heat is taken away by the hydrocarbon coolants used to protect the tuyeres. Thus, Q-BOP can melt about ~ 4% less scrap than a top-blown converter. Reproducibility of the thermochemical reactions is much higher in bottom blowing as the absence of an oxygen lance provides better control of the end point. Turned-down steel has slightly higher hydrogen due to the use of hydrocarbons. The levels of carbon, sulfur, and nitrogen in the steel and the amount of FeO in the slag are, however, less in the bottom-blowing process, compared with the top-blowing. Bottom-blown processes typically have a higher bottom-furnace erosion rate and decreased furnace availability due to high heat generation in the vicinity of the tuyeres.

Combined-Blowing Process. The advantages and limitations of bottom-blown processes over the top-blown classical BOF led to the development of combined-blowing processes where gases are blown both from the top and bottom of the converter, as shown in Fig. 8. Several patented schemes exist under this broad category of steelmaking, which are different only in the type and amount of gases blown from the top and bottom. Some processes also differ in the style of the tuyeres used, such as small uncooled tuyeres, cooled tuyeres, or permeable elements. Oxygen is typically blown through the top lance with either inert stirring gas (LD-KG, LD-AB, and LBE processes), inert oxidizing gas (LD-OTB, LD-STB, and BSC-BAP processes), or oxygen gas (LD-OB, K-BOP, and OBM processes), blowing through the bottom. Processes, such as Krupp-COIN, and KMS, which have the flexibility to operate on a 100% scrap charge, are also categorized as combined-blowing processes. These methods are characterized by the means employed for increasing the scrap melting rate using a post-combustion lance, scrap preheating, and/or carbon injection.

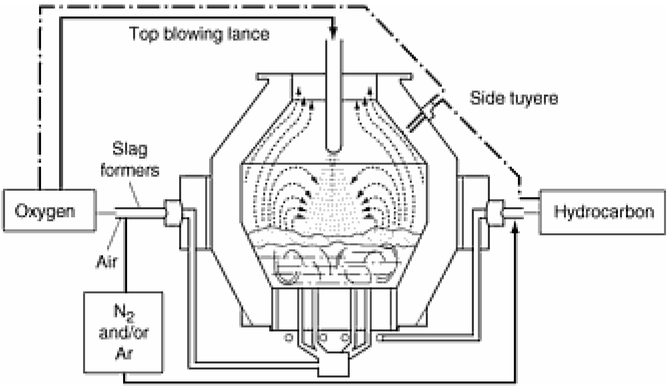

Fig. 8 Schematic representation of a combined-blowing process

Processes that employ submerged-gas injection to increase bath agitation help increase decarburization efficiency while decreasing oxidation of the metals in the bath. These processes also reduce dissolved oxygen levels and flux consumption while allowing a higher manganese retention. Lower dissolved oxygen in combined blowing through permeable elements at any given carbon level with respect to top-blown processes allows better recovery of the alloying elements and decreases the need for deoxidizers in ladle metallurgy. Lower oxygen is the result of better mixing and near-equilibrium refining of steel in combined-blowing processes. Combined-blown processes have ~1.0% higher yield due to less oxidation of iron and manganese and a lower slag rate. Lower oxidation of metallics result in a lower scrap rate for the process. Processes using cooled bottom tuyeres allow the injection of hydrocarbons, powdered lime, or coal to enhance the refining rate and scrap melting. Use of uncooled small tuyeres at the bottom using argon gas injection for stirring is limited due to the cost of argon and the clogging effects at high argon flow rates.

Process Control. Significant online computerized process control capabilities are available for steelmaking depending on the final product mix, decarburization reactions, metallurgical requirements of the plant, and the response time for corrective actions. Carbon removal rate, carbon level, and bath temperature can be continuously monitored. Some measurements use models that call for consistency in the shop practices and quality of materials used, as well as close adherence to the computer recommendations. Online process control results in improved control of carbon, sulfur, and phosphorus amounts and tapping temperature, decreased heat time, increased scrap rate and heat size, decreased flux, coolant, and oxygen consumption, and an overall improved quality of steel. Precise control of the end point carbon and the temperature eliminates time consuming and expensive reblow or cooling procedures.

The static-charge model prescribes the proper combination of the charge materials--hot metal, scrap, fluxes, and oxygen--required to meet the desired end point composition and temperature. Part of the calculations are completed in advance, and trimming calculations are done when the actual material balance is available. Calculations also occur during the heat to determine the reblow or cooling requirements to get to the desired end point. Dynamic procedures using in-blow measurements are used for precise control of 100% of the heats in combination with the static charge models. Water-cooled sub-lance systems to measure online carbon and temperature, off-gas analysis with continuous recomputing of carbon level, and sonic analysis for carbon level through sound intensity are some of the methods practiced industrially. Immersion thermocouples usually provide the direct temperature measurement.

Refractories in Iron and Steelmaking

Refractories are the primary materials used by the steel industry in the internal linings of furnaces for making iron and steel, such as blast furnaces, BOF, EAF, etc., and in ladles and tundishes for holding and transporting metals and slags. Thus, the refractories are often required to withstand temperatures in excess of 1700 °C (3090 °F). Refractories affect the quality of the product as well as the energy consumption in iron and steelmaking. Refractories are chosen on the basis of service life and cost.

Basic Refractories. The most important group of refractories for the basic steelmaking processes are magnesite-based and are either natural or synthetic magnesite, brucite, and dolomite. Dense synthetic magnesia is produced from sea water and has a purity of 95 to 99% MgO. Natural magnesite is present as a hydroxide or a carbonate. The double carbonate of dolomite ($CaCO_3 \cdot MgCO_3$), is found in abundance. High-temperature calcining (firing in kilns to dissociate the carbonates) is required in all the cases to produce a dense material with minimum impurities. Magnesia-chrome refractory spinels are also commonly used without firing in combination with magnesia refractory.

Acid Refractories. The siliceous group of refractories that fall under the "acid" class of materials are beneficiated from quartzite, sandstone, or zircon-type raw materials. Electrical fusion is used to produce special-purpose refractories of fused silica or stabilized zirconia. Several types of fireclays, hydrated aluminosilicates, and kaolin firebricks are usually used for low-temperature refractory needs. The plasticity of fireclays allows it to be used for sealants and grouts.

Other Refractories. Alumina refractory bricks, as high-alumina silicates or pure sintered alumina, are common for high-temperature refractory applications. Carbon bricks and blocks made from petroleum coke, foundry coke, or anthracite coal are extensively used as furnace hearth lining. Silicon carbide and silicon nitride refractories, produced by firing coke and silica mixtures at high temperature, are used in pure form as well as in combination with other refractory materials.

In general, refractories are required to withstand a wide range of temperature and sudden changes in temperature to accommodate the thermal shock. Resistance to small compressive stresses, abrasive forces, corrosive actions of molten metal, slag, and process and effluent gases is required. In addition, refractories are required to function as an insulator, heat absorber, or a heat conductor depending on the application. Chemical and physical characteristics of iron and steelmaking refractories, as well as the selection of lining materials for different reactors, have been discussed elsewhere (Ref 22).

Fluxes in Iron and Steelmaking

The function of fluxes in iron and steelmaking is twofold: (1) to render the high melting refractory oxide impurities or gangue fusible and separable from the molten metal, and (2) to provide a medium with which the impurity elements or compounds would combine in preference to the metal. Practically all of the slag-forming compounds that enter a smelter or refiner can be classified as basic or acid. Silica is the only substance used as a strictly acid flux, although in slags phosphorus oxide behaves in a strongly acidic manner. Neutral fluxes are sometimes added to improve the fluidity or to lower the melting point of the slag for better reaction kinetics and slag handling. Ores contain both acidic and basic oxide impurities with the acidic component predominating. Amphoteric oxides, such as alumina and titania, have a basic or an acidic nature, depending on the slag condition. In acid steelmaking processes, silica is often picked up from the furnace lining itself. In basic processes, such as BOF or EAF, silica is added when excess lime or insufficient silica is present in the system.

Primary basic fluxes are either limestone ($CaCO_3$) or dolomite (($(Ca, Mg)CO_3$) and either or both can be used as a blast-furnace flux, depending on the other slag constituents present and the required ability of the slag to remove sulfur. Limestone is preferred for large sulfur removal. The basic oxygen steelmaking process uses burned or calcined lime or burned dolomite to flux silica produced by silicon oxidation. The presence of magnesia in the slag helps protect the magnesite brick lining of the furnace. Limestone and dolomite are precalcined or burned outside the steelmaking vessel, because dissociation of these compounds is endothermic, and an extra heat load on an autothermal process is not desired. Burned lime contains >95% CaO, and the calcined dolomite is comprised of >57% CaO and >40% MgO. Fluorspar or calcium fluoride with >50% CaF_2 is used in steelmaking as a more efficient desulfurizer. Quality and quantity of fluxes in iron and steelmaking are important as they occupy a useful volume in the reactors and influence productivity.

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Secondary Steelmaking

Ladle Metallurgy

Secondary steelmakings, or ladle metallurgys, is performed to produce clean steel. Clean steels satisfy stringent requirements of surface, internal, and microcleanliness quality and of mechanical properties. The secondary step of ladle metallurgy follows the primary refining in a converter or an EAF, as described in the previous section. Ladle metallurgy has become a routine part of steelmaking due to the growing stringent requirements on the steel composition. Ladle metallurgy is used for deoxidation, decarburization, and adjustment of chemical composition including gases. Refining times in the furnace can often be shortened and production rates increased with an efficient secondary steelmaking practice. Ladle metallurgy also allows the control of teeming temperature, especially required for continuous casting. Steels with as low as 0.002 wt% S can be produced free of oxide or sulfide inclusions. Inclusion shape control is also performed in ladles to improve mechanical properties.

Deoxidation and Alloying. Steels are required to meet certain temperature and chemical requirements for proper ladle metallurgy. Toward the end of tapping some amount of furnace slag is carried over into the ladle. Deoxidation and alloying additions can be made during tapping. Intense agitation of the bath caused by the falling stream of liquid metal helps in alloy dissolution, deoxidation, and homogenization. Loss of deoxidizing elements added, such as aluminum and silicon, depends on the amount and composition of the carried-over slag (Ref 23). The loss of deoxidants is minimized as they are expensive, and the entrapment of deoxidation products adversely affects steel cleanliness. Typically, a deoxidant, such as aluminum, would be partly oxidized by the furnace slag and the entrained air. Aluminum is also dissolved in steel depending on the existing equilibrium condition. The primary role of aluminum as a deoxidant is to react with the dissolved oxygen and float up as alumina. However, some of the finer alumina particles are retained in the steel as inclusions. Making low-inclusion steels requires further treatment to float the fine oxide particles. Slag carry-over is minimized to control the hydrogen and nitrogen pick up by the steel as well as the phosphorus reversal due to reduction of P_2O_5 by deoxidizing agents. Several types of devices are available as slag stoppers.

Argon Rinsing and Vacuum Treatment. Stirring treatment with argon gas, also known as online argon rinsing, can be done to homogenize the bath and to promote decarburization by lowering the carbon monoxide partial pressure. Argon rinsing also helps in lowering the nitrogen and hydrogen content, as well as enhancing alloy dissolution and slag-metal reactions due to stirring effects. Exchange treatments with synthetic (low FeO) slags (Ref 24) or conditioned (high CaO) slags (Ref 25) can be carried out during or before tapping followed by argon rinsing to promote deoxidation, desulfurization, and inclusion modification. Methods for argon rinsing are shown schematically in Fig. 9. Although a stopper-rod arrangement is shown in Fig. 9 for teeming the ladle, use of slide-gate systems are more prevalent now.

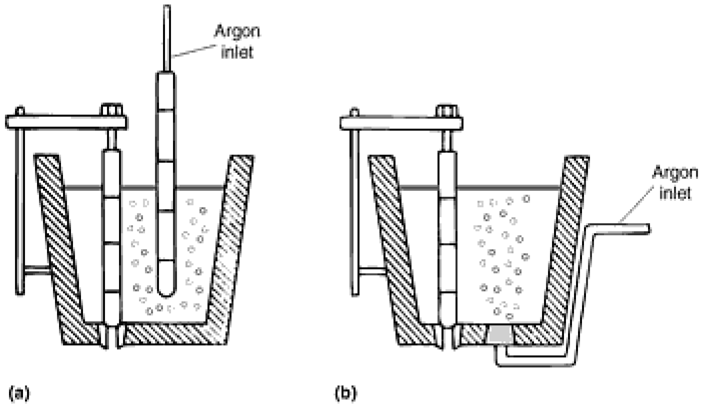

Fig. 9 Schematic illustrating methods for using the argon-stirring process. (a) The lance method. (b) The porous-plug method

Vacuum treatment is done to facilitate degassing and enhance the kinetics of deoxidation and decarburization. Alloy additions can also be made during the vacuum treatment. Alloy additions susceptible to oxidation, for example, iron-niobium, are added after deoxidation. The recovery of expensive alloys is improved by ensuring complete dissolution. Injection treatment in ladles with inert gas, inert gas-oxygen mixtures, or pure oxygen is practiced. Injection of powdered agents of CaSi, CaC_2, CaAl, rare earths, and magnesium with an inert gas carrier, or of submerged cored wire with a prior synthetic slag treatment allows for simultaneous deoxidation, desulfurization, and sulfide shape control. If ultra-low carbon steel grades are to be produced, deoxidation is usually not performed at the time of tapping since dissolved oxygen is later required to react with carbon.

Accurate assessment of temperature, chemical composition, and quantity of steel in the ladle must be known for efficient secondary processes. The use of high-quality refractories in the liquid steel handling facilities are desirable to achieve lower oxygen activity when steel is contained in ladles or tundishes. Ladle preheating and temperature control is an integral part of secondary steelmaking as ladles essentially act as heat sinks.

Synthetic Slags. Ladle refining to produce ultraclean steels and efficient desulfurization are achieved when steel is treated under a basic, nonoxidizing slag. These synthetic slags have low oxygen potential, low melting point, moderate fluidity, and high solubility for alumina and sulfur.

Processes and Objectives

Secondary steelmaking processes define the ways in which the liquid steel is handled in order to achieve the objectives. Table 2 lists the primary methods and equipment used for ladle treatment and their relative capabilities. These methods can be categorized under four major groups (Fig. 10): stirring, injection, vacuum, and heating processes (Ref 26, 27).

Table 2 Relative efficiency of secondary steelmaking processes

0, none; 1, good; 2, better; 3, best

Steelmaking processes	**Metallurgical functions**							
	Composition control	**Temperature control**	**Deoxidation (O_2)**	**Degassing (H_2)**	**Decarburization**	**Desulfurization**	**Microcleanliness**	**Inclusion morphology**
Stream degassing	1	0	1	3	1	0	1	0
D-H degassing	2	2	2	2	2	0	2	1
R-H degassing	2	2	2	2	2	0	2	1
RH-OB degassing	2	2	2	2	3	0	2	1
Ladle refining furnace, reheat only	3	3	3	0	0	1	3	0
Ladle refining furnace, reheat and vacuum degassing	3	3	3	2	2	3	3	1
Argon-oxygen decarburization	1	2	2	1	3	2	1	1
Argon bubbling, CAS	2	1	1	0	0	0	1	0
Argon bubbling, CAB	2	1	2	0	0	2	2	2
Lance powder injection	1	0	2	0	0	3	2	3
Cored-wire injection	2	0	2	0	0	1	2	3

REM canister	1	0	1	0	0	1	1	3

D-H, Dortmund-Horder-Huttenunion; R-H, Ruhrstahl-Heraeus; CAS, composition adjustment by sealed argon bubbling; CAB, capped argon bubbling; REM, rare earth metals

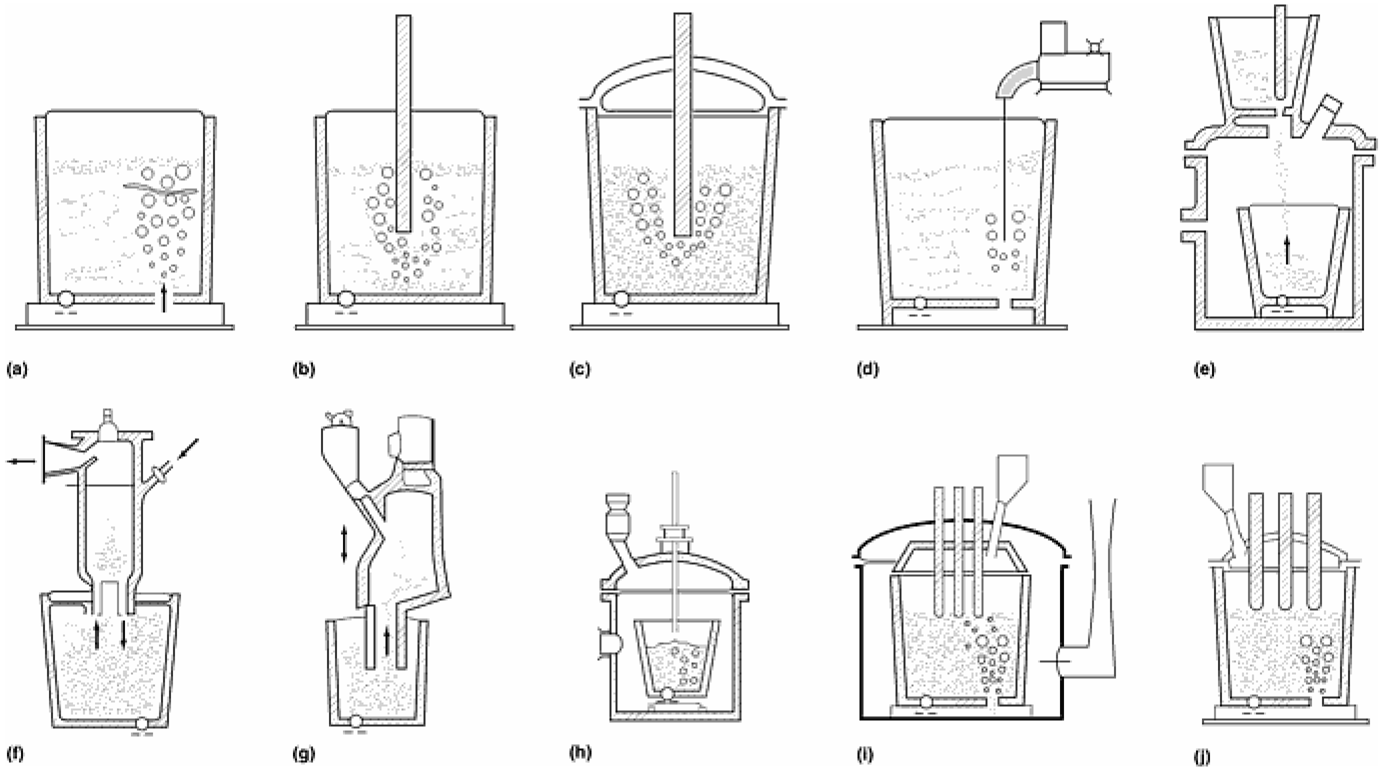

Fig. 10 Processes for secondary steelmaking. Stirring process: (a) bottom injection and (b) lance injection. Injection processes: (c) powder injection and (d) wire feeding. Vacuum processes: (e) stream degassing, (f) R-H degassing, and (g) D-H degassing. Heating processes: (h) VOD process, (i) VAD process, and (j) ladle furnace process

Stirring is simple purging or rinsing of liquid steel by inert argon gas passed either through a porous plug or a submerged lance (Fig. 9) to achieve bath homogenization and oxide flotation. Deoxidation and desulfurization by enhancing slag-metal reactions can also be achieved by argon purging if a synthetic slag is used. Alloy additions or deoxidation reagents are introduced either in a powder form through a submerged lance with the help of a carrier gas or by encasing the materials in a wire by injection metallurgy. Vacuum processes are designed to reduce the partial pressure of hydrogen, nitrogen, and carbon monoxide gas in the ambient atmosphere to enable degassing, decarburization, and deoxidation. Vacuum treatments can be broadly classified into vacuum stream degassing, ladle degassing, and recirculation degassing (Table 2 and Fig. 10). The loss in temperature during secondary treatment is compensated by either using a higher superheat in the primary steelmaking or by an additional reheating process, such as the ladle furnace with submerged electrodes. Vacuum-induction melting or vacuum-oxygen degassing are other examples of heating processes. Some of the prominent processes are described in greater detail later in this section and in the section "Processing of Special-Quality Steels."

Treatments

Degassing. Liquid steel absorbs gases from the atmosphere and from the materials used in steelmaking and can cause embrittlement, voids, inclusions, etc., in the steel when solidified. The major gases to be eliminated are oxygen, hydrogen, and nitrogen. Oxygen is the principal refining agent in steelmaking and plays a role in determining the final composition and properties of steel and influences the consumption of deoxidizers. The production of rimmed, semikilled, or killed grades of steel essentially refers to oxygen management in liquid steel before solidification. If the oxygen content of molten steel is sufficiently high during vacuum degassing, the oxygen will react with some of the carbon to produce carbon monoxide. The evolved carbon monoxide is removed by the created vacuum, known as vacuum-carbon deoxidation. In undeoxidized steel, the carbon and oxygen contents approach equilibrium at a given temperature and pressure according to:

$$\mathrm{C} + \mathrm{O} \leftrightarrow \mathrm{CO}\ (\mathrm{gas}) \qquad \textbf{(Eq 11)}$$

$$K^{eq}_{1600\ ^\circ C} = \frac{p_{CO}\ (\text{atm})}{\text{wt\% C wt\% O}} \quad \textbf{(Eq 12)}$$

where K^{eq} is the thermodynamic equilibrium constant and p_{CO} is the partial pressure of carbon monoxide.

Figure 11 shows the contents of carbon and oxygen in equilibrium at 1600 °C (2910 °F) as a function of partial pressure of carbon monoxide. As the pressure is lowered by vacuum treatments, more and more carbon reacts with oxygen to establish the new carbon monoxide partial pressure, thus making the oxygen unavailable for inclusion formation with the added deoxidizers. Strong deoxidizers, such as aluminum, titanium and silicon, react with oxygen with greater affinity than carbon at atmospheric pressure (Fig. 12) so carbon cannot react with oxygen when vacuum degassed. If not floated properly, oxides of deoxidants can result in inclusions when solidified. Carbon is a stronger deoxidizer than aluminum, titanium, or silicon below a pressure of 0.01 atm.

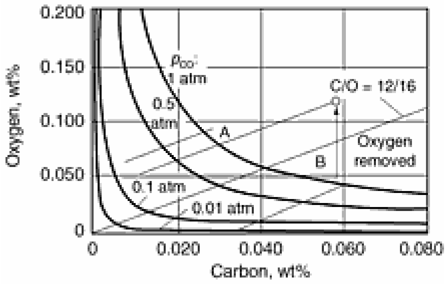

Fig. 11 Carbon-oxygen equilibrium relationship in liquid steel at 1600 °C (2910 °F) for various partial pressures of CO gas above liquid steel. If carbon and oxygen levels are at 0.04 and 0.05 wt%, respectively, at the start of vacuum treatment (region A), then enough oxygen is available to lower the carbon content to 0.01 wt% at p_{CO} of 0.01 atm. However, for carbon levels greater than 0.05 wt% (region B), an external oxygen source is necessary before vacuum treatment to raise the oxygen level to region O, if 0.01 wt% carbon is desired in the steel at p_{CO} of 0.01 atm. Note that regions A and B are above and below the CO gas stoichiometric line, respectively.

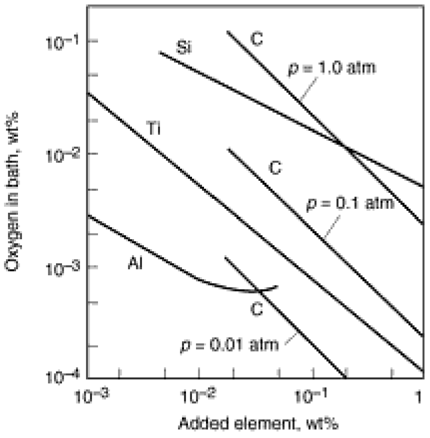

Fig. 12 Equilibrium relationship between the contents of total oxygen and various deoxidizing elements in a steel bath

Hydrogen causes bleeding ingots, embrittlement, low ductility, thermal flaking, and blowholes. Hydrogen is usually picked up from the moisture in the charge and the environment and can be lowered by an effective vacuum treatment, according to Sievert's law:

$$[\%H] = K\,(p_{H2})^{1/2} \quad \textbf{(Eq 13)}$$

The amount of hydrogen dissolved in molten steel, [%H], is related to the partial pressure of hydrogen gas above molten steel, p_{H2}. The equilibrium consant K is equal to 0.0027 at 1600 °C (2910 °F). Hydrogen removal during vacuum degassing is affected by factors such as surface area exposed to vacuum, degassing pressure, steel composition, extent of prior deoxidation, and hydrogen pickup from alloy additions, slags, and refractories.

Nitrogen is particularly harmful for low-carbon steels intended for drawing applications and should be lowered as much as possible. Although nitrogen follows Sievert's law, its removal by argon flushing or vacuum degassing is limited due to the tendency of nitrogen to form stable nitrides. Primary control of nitrogen is attempted during steelmaking practices.

Decarburization. It is difficult to produce steel by conventional steelmaking with <0.03% C. Carbon can be lowered to 0.01% from 0.04 to 0.06% levels by simply exposing it to a vacuum, as shown in Fig. 11. Particular attention must be paid to the amount of carbon in alloying additions made after decarburization of steel.

Desulfurization. It was mentioned previously that primary steelmaking has very limited capability in removing sulfur from steel due to the highly oxidizing conditions present. However, ladle processes do allow for external desulfurization by judicious selection of an agent.

Oxygen is a deterrent in sulfur removal and, therefore, should be pre-deoxidized to the lowest practicable oxygen content, preferably with aluminum. Simultaneous deoxidation and desulfurization is also commonly performed. Efficiency of desulfurization is lowered by the carry over of oxidizing furnace slags as the oxides are unstable during the sulfur removal treatment. In addition, FeO lowers the desulfurization efficiency. Similarly oxides in the ladle lining can affect the efficacy of sulfur removal. Because desulfurization involves slag-metal reactions, intimate mixing of steel and desulfurizing agents is a prerequisite. In addition to the previous requirements, the initial and final levels of sulfur are critical according to the law of mass action. Thus, steels with less than 0.006% S are difficult to make.

Secondary Steelmaking Equipment

Secondary steelmaking is usually performed in a ladle, vessel, or special furnace to achieve refinements that cannot be done in the primary reactor. A primary reactor is emptied into a tapping ladle, and then the steel can be transferred into other ladles, furnaces, or vessels for treatment. Alternatively, the steel can be treated in the tapping ladle before being poured into molds.

Vacuum Degassing Processes. The processes where liquid steel is exposed to a low-pressure environment to decrease gaseous content, particularly hydrogen and oxygen, are referred to as vacuum-degassing processes. The effectiveness of these methods is directly linked to the surface area of molten steel exposed. As described earlier, hydrogen removal is dependent on the partial pressure and diffusion, whereas oxygen removal primarily relies on the chemical reaction between carbon and oxygen and the partial pressure of carbon monoxide gas. These processes also accomplish composition and temperature control, decarburization, microcleanliness, and inclusion morphology control. Vacuum degassing is accomplished primarily by three methods: (1) stream degassing, (2) recirculation degassing, and (3) vacuum degassing in the ladle.

Because heat losses during degassing occur through radiation and absorption of heat by ladles or vacuum vessels, and because heat losses vary for different processes, tapping temperature of the steel must be adjusted for compensation of temperature losses. Ways of conserving heat during vacuum processing are the retention of a slag layer on the molten steel surface, use of radiation shields, vessel preheating, supplemental heating arrangements, and optimization of processing time. The vacuum in most modern degassing systems is created by steam ejectors installed in series to provide multistage pumping capability. A greater number of pumping stages are used for low-carbon steels in the partly deoxidized condition than for deoxidized high-carbon steels when treated at the same rate. A reheating type vacuum-induction melting process uses up to six stages, whereas a recirculating type R-H (Ruhrstahl-Heraeus) or D-H (Dortmund-Horder-Huttenunion) degasser uses five. A four-stage steam ejector is common for other vacuum degassing systems. Moreover, vacuum-degassing processes allow the addition of deoxidizers and alloy additions to the molten steel while under reduced pressure. These additions are optimized for the capability of the system to manage the heat and mixing.

Stream degassing methods include ladle-to-ladle, ladle-to-mold, and tap degassing. Ladle-to-ladle degassing achieves hydrogen removal as well as oxygen removal by carbon deoxidation. A preheated teeming ladle with either a slide-gate mechanism or a nozzle and stopper-rod arrangement is placed inside the tank, and the opening in the tank is covered with an aluminum disk. The tank is evacuated to 0.1 torr, and a superheated, partly deoxidized steel in the tapping ladle is placed on top of the evacuated tank. The stream of molten steel from the tapping ladle melts the aluminum disk cover and flows into the teeming ladle while other deoxidants are added through the addition hopper under vacuum. The pressure stabilizes at ~0.8 torr during degassing. Nitrogen is used to bring the system back to atmospheric pressure after degassing.

In the ladle-to-mold degassing, an ingot mold is placed on a base, fitted with hot top, and preheated using burners. The vacuum tank is placed around the base and makes a vacuum tight seal. A transfer or "pony" ladle, fitted with stopper rod and nozzle assembly, is placed in line with the mold inside the tank. A preheated refractory collar is fitted into an opening in the top of the tank to direct the pouring stream from the pony ladle nozzle into the mold. The tank is evacuated to 0.10 to 0.20 torr, and the tapping ladle containing the superheated steel is placed above the pony ladle for bottom pouring of steel. Once the pony ladle is two-thirds full, the stream of steel is allowed to enter the tank through the collar. The stream breaks up into tiny droplets after entering the vacuum chamber and attains a very large surface area enhancing the degassing process. Several tapped steel heats can be vacuum cast into large ingots by this method. Nitrogen or air is allowed into the tank to break the vacuum.

Tap degassing consists of a special ladle with a flange at the top and an "O"-ring seal plate for the nozzle opening at the bottom, a ladle cover, and a stoppered tundish having an aluminum-disk seal just below the nozzle. The nozzle is sealed, and the special ladle is covered with the lid. An alloy addition hopper is inserted through the ladle cover. The preheated stoppered tundish is placed on top of the ladle cover, and the entire assembly is positioned such that the tapping stream from the steelmaking furnace can be captured in the tundish. The ladle is evacuated to 0.2 to 0.5 torr, and the stopper rod of the tundish is pulled when the tundish is full with the superheated steel tapped from the furnace. The required deoxidizers are added through the hopper during degassing. After degassing, the ladle is restored to atmospheric pressure and teemed by conventional methods described in the section "Casting."

Recirculating degassing methods use atmospheric pressure to force the liquid steel from a ladle into an evacuated chamber where it is exposed to low pressure and then flows back into the ladle. The metal can recirculate 40 to 50 times to achieve degassing where the vacuum is used to recirculate the metal stream as well as to degas. A refractory-lined vacuum vessel with a "snorkel" tube, an electric-resistance graphite heating rod, an alloy addition hopper, a mechanism to lower or raise the vacuum vessel or ladle, and a steam-ejector system comprise the D-H degassing method (see Fig. 10g). The vacuum vessel is internally preheated to the desired temperature, and the alloying additions are placed in the hopper. The superheated steel is tapped in an unoxidized or partially oxidized condition in a ladle and placed beneath the vacuum vessel. Either the ladle or the vacuum vessel are moved vertically. The snorkel is immersed in the molten steel, and the vacuum vessel is evacuated, causing the steel to be sucked into the vessel. Once the steel is degassed, the snorkel is raised, causing the steel to partially run back into the ladle. The gases are sucked out of the vessel at this stage. Several cycles of this operation degasses the steel to the desired level. Alloy additions are subsequently made before the vacuum vessel is returned to atmospheric pressure. Some snorkels are designed to allow the passing stream of steel to be exposed to argon or oxygen.

Two legs or snorkels are used in the R-H process where one leg is fitted with a gas-inlet pipe (see Fig. 10f). The preheated vessel, similar in construction to the D-H degasser, is lowered in the molten steel ladle containing the superheated steel until ~150 mm (6 in.) of both the legs are immersed. The vacuum chamber is evacuated, and an inert gas is introduced through the gas-inlet pipe and the lower density of the gas-liquid mix causes the steel to rise and flow into the vacuum vessel. The metal is deoxidized and returned to the ladle through the other leg under gravity. Several cycles of this process at a pressure of 0.3 to 0.6 torr degasses steel to the desired level before conventional casting. A variation of the R-H process, known as RH-OB process, is used primarily to remove hydrogen and carbon from steel. The difference between the R-H and the RH-OB processes lies in the gases injected into the system during the process of degassing. The RH-OB process also introduces oxygen, in addition to an inert gas into the system to enhance decarburization. Inert gas also helps in stirring the melt.

Vacuum ladle degassing processes include induction stirring and vacuum-oxygen decarburization (VOD). In the induction stirring process, induction coils are used to induce eddy currents in the molten steel to produce a stirring effect. Steel is contained in a ladle with shell sections made of nonmagnetic austenitic stainless steel and lined with high alumina or basic refractory. Superheated, fully deslagged, non-deoxidized steel is tapped at a relatively higher temperature than other vacuum degassing processes. The ladle is placed inside the induction coil positioned inside the vacuum chamber, a heat radiation and splash shield is placed on the vacuum tank, and the chamber is evacuated slowly to 0.1 torr. During degassing, the induction coils are energized to stir the steel. Alloy additions, primarily ferrosilicon, aluminum, and carbon, are added through a hopper towards the end of degassing. Stirring is continued for a few minutes to mix the alloys. After the vacuum tank is returned to atmospheric pressure, a synthetic slag is placed on top of the steel surface to conserve heat and prevent reoxidation.

The VOD method was designed for the production of stainless steel. A stainless steel heat is prepared by charging and melting ferrochromium, stainless steel scrap, ferrosilicon, burned lime, and fluorspar and then heating it to the tapping temperature. The stainless steel is tapped in a preheated basic-lined ladle equipped with porous plugs for blowing argon. The ladle is placed inside a vacuum chamber and evacuated to low pressures while oxygen is lanced above the steel bath and argon is bubbled through the bottom plugs in the ladle (see Fig. 10h). After the oxygen blowing period, further decarburization and deoxidation can be accomplished by additional vacuum time. Deoxidants could also be added during vacuum if desired. A desulfurizing slag can be added to the heat after the vacuum treatment, enabling the removal of up to 50% of initial sulfur. Argon blowing through bottom plugs can be replaced with induction stirring.

Injection Metallurgy. The primary objective of introducing powdered reagents into liquid steel, with the help of either a cored wire or carrier gas, is for desulfurization, deoxidation, alloy dissolution, and inclusion shape control. A wide variety of powders, mechanically mixed or premelted and granulated, are used in industry. Calcium silicide treatment is most prevalent for simultaneous sulfur and inclusion shape control. Lime, alumina, and fluorspar mixtures are also injected to form the synthetic slag. Alloy additions that are usually made through injection include, Fe-Si, $CaCN_2$, graphite, NiO, MoO_2, lead, tellurium, and ferroalloys of Fe-B. Fe-Ti, Fe-Zr, Fe-W, etc. Several commercial systems are available for powder injection through a lance as well as for cored-wire feeding.

When a powder is fed through the lance in the steel melt, particles are accelerated by the high velocity of the carrier gas upon entering the gas stream. For example, in gas-borne powdered injection with the help of a submerged lance, 0.6 to 1.0 mm (0.02 to 0.04 in.) Ca-Si particles are injected at a carrier gas pressure of 5 to 15 atm. At the lance tip, the gas expands as a result of a pressure drop and rise in temperature. In most steelmaking applications, jetting usually occurs during the injection, which is in the form of a gas-jet cone. On leaving the nozzle, the particles travel in a straight line downward due to their high momentum until the jet breaks up into a swarm of rising gas bubbles. The majority of the powder particles are trapped in the rising gas bubbles. If the powder particles are wetted by liquid steel, they can break away and be recirculated in the melt. A slag-metal-gas emulsion thus forms near the top surface. Wire feeding allows the introduction of additions at the bottom of the ladle and, therefore, a better alloy recovery. Injection metallurgy is also used for addition of deoxidants, such as aluminum, in the form of wire feeding as well as lance injection. The initial capital investment for a powder injection installation is much more than that for a wire feeder, but cored wires are more expensive than ordinary metal or alloy powders. Figures 10(c) and 10(d) show a schematic of the injection processes.

Sulfur and Phosphorus Control

It has been emphasized that the primary removal of sulfur is affected during ironmaking in the blast furnace where reducing conditions prevail. However, in steelmaking, direct oxidation at the gas-metal interface in the jet impact zone causes 15 to 25% of dissolved sulfur to directly oxidize into the gaseous phase due to the turbulent and oxidizing conditions existing in the impact zone. Regression equations based on operational data are employed to predict the end-point sulfur within acceptable limits (Ref 28):

$$(\%S)/[S] = 1.42B - 0.13\,(\%FeO) + 0.89 \qquad \textbf{(Eq 14)}$$

where B is the slag basicity defined as the ratio of the weight percents of basic to acidic slag components. For example, $(CaO + MgO)/(SiO_2 + Al_2O_3)$, (%FeO), and (%S) are FeO and sulfur concentrations in the slag, respectively, and [S] is the sulfur concentration in the metal. Desulfurization and inclusion morphology control are accomplished through injection metallurgy in secondary steelmaking. In essence, a powdered reagent, such as Ca-Si, CaC_2, magnesium, $CaO+CaF_2$, or $CaO+Al_2O_3$, is introduced into the liquid steel with the help of a cored wire or a carrier gas. Desulfurization during powder injection with carrier gas has been described using a reactor model (Ref 29).

If the synthetic slag used in ladle metallurgy has a high sulfide capacity, sulfur removal can be accomplished to ultralow levels of 10 ppm sulfur. If the activity of alumina in the slag is low, then the deoxidation product alumina can then be absorbed in the top slag. Thus calcium aluminate type synthetic slags (typically 50 CaO:7 SiO_2:43 Al_2O_3) can deoxidize and reduce total oxygen in the steel as well as desulfurize, simultaneously. Several empirical relationships have been developed to relate the slag composition to the sulfide capacity (Ref 30). Melting and mixing of slag is as important as composition. Premelted slags are commonly used. Vigorous argon stirring of the metal-slag emulsion is necessary for proper deoxidation and desulfurization. Top slag heating is also performed in practice to prevent a thermal gradient in the slag layer. Alternatively, an exothermic mixture of burned lime, hematite, and aluminum powder is used, which helps lower the sulfur content of steel to 0.003 wt% or less, when strongly stirred with argon.

The partitioning of phosphorus between the slag and metal is very sensitive to process conditions in steelmaking. An empirical relationship is used to define the phosphorus partitioning parameter, k_{ps} (Ref 31, 32):

$$\begin{aligned} k_{ps} &= ((\%P_2O_5) \times (1 + (\%SiO_2))/[\%P] \\ &= f((\%FeO),B) \end{aligned} \quad \textbf{(Eq 15)}$$

where B is the slag basicity, ($\%P_2O_5$), ($\%SiO_2$), and ($\%FeO$) are the respective oxide contents in the slag, [%P] is the level of phosphorus in the metal, and f is the function of FeO and B. k_{ps} is independent of basicity for $B > 2.5$. The distribution of phosphorus is also linked to the turn-down carbon level. In general, high basicity and low temperature favor dephosphorization. The addition of fluxes, for example, ilmenite, fluorspar, lime, etc., to lower slag viscosity, also helps to lower the metal phosphorus content. Phosphorus can be essentially captured in the slag during early stages of steelmaking through judicious adjustment of both the blowing practice and hot metal silicon level (Ref 33). Thus, phosphorus control in secondary steelmaking refers to the control of phosphorus reversal occurring through the use of synthetic slags, which is dependent on the activity of P_2O_5 in the slag and the amount of aluminum and silicon in the metal. The Perrin process was developed for ladle dephosphorization using appropriate synthetic slags. It is important to do a slag-free tapping if synthetic slag-aided deoxidation with aluminum or silicon is carried out. The kinetics of deoxidation by aluminum in an argon-stirred vessel or a R-H degasser has been reported in literature (Ref 34).

Inclusion Shape Control

If nonmetallic inclusions must remain in the steel, they should be made innocuous to the desired steel properties by changing their shape and/or composition. Steels can be made with more isotropic properties by changing the "stringer" sulfides to globular sulfides by a calcium compound or rare-earth metals treatment. Ladle injection technology, as described earlier, is an appropriate method for adding rare earths by the plunging method. The calcium treatment, primarily carried out for sulfur control, also has a modifying effect on inclusion morphology. A complete modification of type II manganese sulfide inclusions (Fig. 13) takes place when the sulfur content is <0.07%. In practice, 0.5 to 0.7 kg per metric ton of steel is necessary for inclusion shape control (Ref 24). These reagents could be wire fed or powder injected. However, for wire feeding, recovery of calcium is three to six times greater than powder injection. Rare earth metals (REM) are very efficient in morphology control (stringer type to globular type), although they only have a minor role in desulfurization. Rare earth metal additions are usually accompanied by a magnesium addition to provide the agitation needed for uniformly distributing the REM throughout the heat.

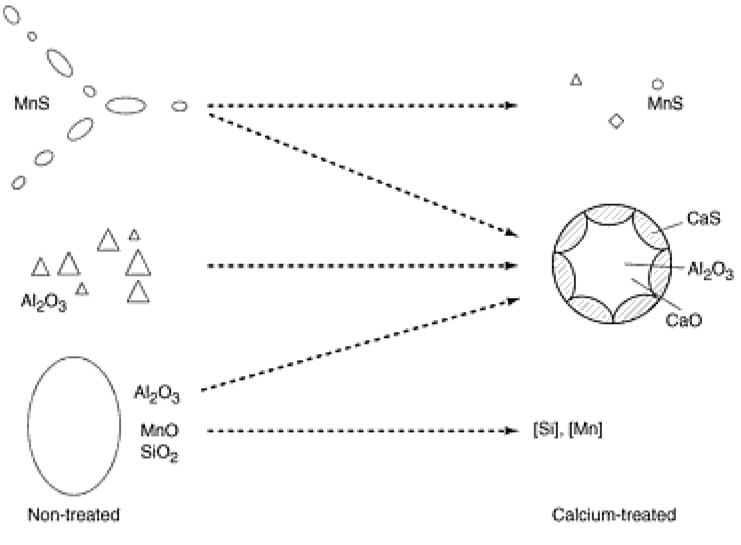

Fig. 13 Schematic representation showing modification of inclusions which calcium treatment

Effect of Residual Elements on Steel Properties

The removal or addition of specific elements in steel is governed by the desired steel properties. Residual solid, as well as gaseous elements in steel, such as sulfur, phosphorus, oxygen, nitrogen, and hydrogen, that are present due to thermodynamic and kinetic limitations in the primary and secondary steelmaking, are mostly undesirable and have a pronounced effect on steel quality and properties. Except for specific grades of steel, a lowering of these elements is preferred. Other elements, such as carbon, silicon, and manganese can be controlled (lowered or raised) to the desired level. Other alloy additions, such as chromium, nickel, titanium, copper, etc., may be present as residuals from the scrap used in steelmaking or as intentional additions to manufacture special alloyed steels. The effect of these elements on the steel properties is briefly described.

Carbon is the primary element in steel that controls the microstructure for any given heat treatment condition either by interstitially dissolving in iron or by precipitating out as a carbide. Carbon is the most economical strengthening element for steel and is used as such. It can impart greater hardness with less accompanying brittleness than any other element in soft steels. Carbon decreases impact resistance of steels. However, it is desirable to keep the carbon content below certain maximum values when arc welding is involved to avoid embrittlement of the heat-affected zone. The choice of carbon level in steel is generally a strategic balance between the desired hardenability and weldability. There are other ways to control these two parameters besides carbon content.

Sulfur injures the rolling qualities of steel by "hot shortness," causing it to crack and tear during rolling and lessening its welding capacity. The harmful effects of sulfur increase with copper content and casting temperature and decrease with manganese content. Sulfur has beneficial effects on the machinability of steel by allowing chips to crumble rather than curl. The presence of sulfur in steel is mostly as elongated sulfide inclusions, which gives rise to anisotropic effects.

Phosphorus. "Cold shortness," or brittleness in the cold condition, is caused by high phosphorus contents and also gives rise to primary segregation tendencies during casting. This effect is enhanced in the presence of high-carbon content. Phosphorus can increase the strength of steel up to a certain extent, although is not used for this purpose due to other deleterious effects. Phosphorus, like sulfur, has a beneficial effect on free machining. Phosphorus is known to help prevent sticking during rolling of steel sheets. In association with copper, phosphorus is also known to improve atmospheric corrosion resistance of steels.

Silicon. High silicon content improves the magnetic permeability of steel and increases electrical resistivity. It improves the soundness of ingots and other castings because it opposes the formation of blowholes and gas cavities. Silicon has been found to slow down the etching rate of ferrite. Silicon helps in improving the atmospheric corrosion resistance of steels, particularly in acid environments. Silicon is known to affect some of the critical thermal points (transformation temperatures), such as Ac_1, Ac_2, Ar_1, Ar_2, etc. (consult the iron-carbon phase diagram for definitions). In general, as silicon content increases, elongation decreases, and hardness, yield point, and tensile strength increase. Silicon can also lower the solubility of graphite in iron considerably.

Nitrogen has a strong strengthening effect and makes the steel brittle. It is used in moderate quantities in sheet steels to impart strength with good formability. Nitrogen promotes quench aging and strain aging in steels which manifest in increased hardness, yield, and tensile strength, reduced ductility, and increased notched impact transition temperature. Dynamic strain aging or "blue brittleness" can occur due to a high nitrogen level. Strong nitride formers, such as aluminum, are often used to prevent strain aging. In high-speed steels, carbonitride formers are used to enhance the abrasion resistance. Nitrogen is also a grain refiner. Vacuum melting of type 304L stainless steel can cause removal of nitrogen and, therefore, grain growth. Often these large grains are of the same order as the thickness of a thin-walled tube.

Oxygen. If present in large amounts, oxygen produces tearing during forging or rolling and makes the steel brittle under shock when cold. Oxygen also occurs in the form of iron and manganese oxides and silicate and aluminosilicate inclusions, which can impair notch toughness of steel if shape control is not employed. Aluminum oxide stringers are very detrimental to rolling contact fatigue resistance in bearing steels. These stringers are more likely to occur in continuous cast material where aluminum wire feeding is performed above the mold as the final deoxidation step. If inclusion removal is not adequate in the mold, aluminum oxide stringers form within the metal.

Hydrogen is present in steel as a dissolved gas or sometimes as dissolved methane or marsh gas. If not degassed properly, hydrogen has a definite embrittling effect and the steel shows a loss in ductility. The ductility can be regained by baking off the hydrogen at a moderate temperature. Hydrogen in excess of 0.005 wt% causes flaking, which is manifested as internal cracks or bursts, usually occurring during cooling from rolling or forging. Hydrogen pickup during welding is a problem for high-carbon, large-section steel pieces. Hydrogen is often associated with delayed brittle cracking of steels under sustained tensile stresses.

Manganese increases strength and improves notch toughness. The amount of manganese above that required to form manganese sulfide, is present as manganese carbide or silicide. Manganese sulfide inclusions upon rolling give rise to "banded" structures. Manganese improves the forgeability or the ability to be rolled through its ability to tie up sulfur. Thus, manganese is the element that turns iron into steel and allows hot working and welding without tearing or hotshortness due to the presence of low-melting iron sulfide. Manganese is known to increase the impact strength of steel and retards the coarsening of grains during high-temperature rolling. Plasticity of steel is also reported to improve by higher manganese content, but the tendency to crack on quenching is enhanced. Manganese is also known to affect the thermal critical points for steels. Manganese is often substituted for carbon to improve the steel weldability. The presence of manganese is essential in steels.

Other Elements. Certain other residual elements, such as nickel, copper, molybdenum, chromium, and tin can be introduced in the steel through the scrap. Aluminum, vanadium, titanium, zirconium, etc., may be present from the deoxidation practice. These elements can also be intentionally added to the steel in varying amounts for achieving particular physical and mechanical properties, such as precipitation strengthening, solution strengthening, enhanced weldability, corrosion resistance, machinability, etc. For example, over 12 wt% Cr is added in steels to render it stainless (corrosion resistant), and nickel stabilizes austenite at room temperature allowing cold workability in 300 series of stainless steels. The effects of these alloying elements are discussed in the section "Specialized Processing Routes" and throughout this Handbook in the sections describing various types of steels.

In brief, nickel, chromium, molybdenum, and copper increase the hardenability of steels and can cause problems for steels requiring high ductility such as deep-drawing applications. These elements also change the heat treatment characteristics. Nickel can serve as a grain refiner and ferrite strengthener in larger quantities and also stabilizes the austenite. At cryogenic temperatures, nickel increases toughness, that is, lowers ductile-to-brittle transition temperature. Chromium generally forms carbides in steels and is known to increase the elastic limit, tensile strength, and hardness of steel while decreasing ductility. Chromium stabilizes martensite. It also has strong beneficial effects on corrosion resistance of steel, although chromium in excess of 12 wt% is required. Molybdenum allows the steel to be heated for forging through a wide range of temperatures without injury. Molybdenum in steels promotes resistance to impact and wear and imparts toughness.

Vanadium, even in very small quantities, increases the tensile strength and raises the elastic ratio without lowering the ductility appreciably. Vanadium increases impact resistance, fatigue strength, and resistance to abrasion. Vanadium prevents grain coarsening through stable carbide precipitation. Tin in small amounts is harmful to deep-drawing steels. Aluminum is generally desirable because it acts as a grain refiner and tends to decrease the susceptibility to strain aging. It, however, promotes graphitization and is harmful for high-temperature applications. Other deoxidizers, such as titanium or zirconium in trace quantities, are generally innocuous to steel properties. Some of the beneficial effects of these elements may require more than trace quantities and, therefore, have to be provided by alloying during secondary steelmaking. For example, titanium, niobium, zirconium, and vanadium may be used as microalloying additions to serve as precipitation hardeners by forming carbides.

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Processing of Special-Quality Steels

Some steels, such as bearing steels, heat-resistant steels, ultrahigh strength missile and aircraft steels, and rotor steels have higher quality requirements and tighter composition control than plain carbon or ordinary low-alloy steels. The production of special-quality steels requires vacuum-based induction or electric remelting and refining capabilities. Because longer durations are required for producing ultraclean steels and often require larger alloy additions, facilities to reheat the steel during secondary steelmaking operations are essential. These methods provide the following benefits:

- Contents of gases, for example, hydrogen, nitrogen and oxygen, are substantially reduced
- Cleanliness is improved, that is, there are fewer nonmetallic inclusions
- Center porosity and segregation in the ingot resulting from ingot casting the process are eliminated because of progressive melting and solidification of steel
- Hot workability of the metal is improved
- Mechanical properties of the remelted steel improves at room temperature as well as elevated temperatures, such as the ductility, impact, fatigue, and creep-rupture strengths

Vacuum Induction Melting (VIM)

Both channel and coreless type induction electric furnaces are used in the steel industry (Ref 35). In the remelting process, the charge material has basically the same chemical analysis as the final melt. No major refining or metallurgical work is performed other than lowering the residuals and inclusions. When remelting alloy steel, certain elements that readily vaporize or oxidize have to be added under controlled conditions. As a rule of thumb, alloying elements that oxidize should be added as late as possible, and difficult-to-dissolve elements should be added early and during high stirring periods. The furnace lining is dependent on the nature of the slag and the desired finish temperature. Vacuum melting is often employed as a remelting operation for very pure steels and as a first stage in a duplex refining operation in which the product from the vacuum induction furnace, for example, VIM, is remelted in either a vacuum consumable-electrode (vacuum-arc remelting, or VAR) furnace or an electroslag remelting (ESR) furnace. These processes are described in greater detail later in this section. Oxygen, hydrogen, and to some extent nitrogen, can be removed during vacuum melting. Carbon can also be lowered to produce some types of stainless steels. Pressures as low as 5 μm of Hg are used in these furnaces. The control of pressure and composition of gas over the melt makes it possible to deoxidize the melt with carbon or hydrogen, because they produce gaseous deoxidation products, preventing the formation of nonmetallic inclusions. Use of low pressures also eliminates nitrogen pickup by steel. The volatility of certain alloying elements such as chromium, aluminum, and manganese can result in high losses that can be minimized by replacing the vacuum with an inert gas atmosphere over the melt during additions.

Modified vacuum induction equipment (such as the Therm-I-Vac process) can be used either as a vacuum induction melter under low pressure or as a stream degasser. The system can be used for cold charging of steel in the induction furnace, and melting, refining, and teeming of steel under low pressure. The steel could also be hot charged under low pressure in the vacuum furnace during which stream degassing occurs, reheated to compensate for the losses during degassing, adjusted for alloy additions to meet the chemical composition specifications, and teemed, all under low pressure. Superheating of steel is not required if hot charging is performed. The steel can be partly deoxidized before charging into the vacuum induction melter. This equipment is mostly used as a vacuum induction unit to melt a cold charge.

Vacuum Degassing with Reheating

Ladle refining furnaces allow the addition of heat to the secondary steelmaking process, which, in turn, allows larger alloy additions required for some special steels and stainless steels. The furnace's ability to provide heat during refining by arc reheating using electrodes provides the capability to desulfurize, deoxidize, and perform metallurgical operations using synthetic slags, as described in the section "Secondary Steelmaking." These furnaces can either reheat or reheat and vacuum degas. The plain heating furnaces can perform composition and temperature control, deoxidation, and facilitate microcleanliness. If the furnace is also equipped to vacuum degas, it can additionally desulfurize the steel. Gas stirring or induction stirring is used in addition to arc reheating as a prominent process design variation. The Finkl-Mohr VAD degassing system uses gas stirring whereas the ASEA-SKF ladle refining furnace uses induction stirring. Gas stirring is designed for desulfurization and other steelmaking refinements including degassing. The process is similar to a ladle vacuum degassing method described in the subsection "Secondary Steelmaking Equipment," except that the steel can be heated before or after the degassing operation using an electric arc provided by electrodes inserted through the vacuum tank cover (Fig. 14). An inert gas is used to stir molten steel in the ladle degassing process.

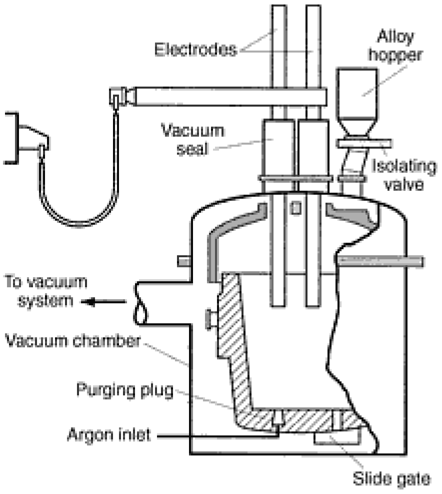

Fig. 14 Schematic arrangement of equipment used in the gas-stirring, arc-reheating process

When induction stirring is performed (ASEA-SKF process), the system comprises a ladle furnace, a mobile induction coil, a vacuum cover with exhaust line, a steam ejector system, and a cover fitted with three carbon electrodes. Sections of the vessel shell are produced from nonmagnetic austenitic stainless steel. The same ladle can be used to tap the heat from the converter and then serve as a heating furnace, vacuum vessel, and teeming ladle. The steel is tapped without superheat and without any deoxidant addition. Slag-free tapping is performed. The ladle is placed in the mobile induction coil and covered with the top containing the three electrodes. The arcs are struck to begin the reheating and refining period. Fluxes are added to prepare a basic slag, and alloy additions are made to meet the compositional specifications. Sulfur is reduced to below 0.005%. Heat loss is restored and the vessel is ready for degassing. The cover is replaced with the vacuum furnace cover, and the vessel is evacuated. Induction coils are energized to stir the steel. Aluminum and silicon are added toward the end of degassing. Following the degassing, the same ladle is moved to the teeming platform for ingot casting, or the steel is poured into a tundish for continuous casting (see the section "Casting").

Vacuum-Arc Remelting

Consumable-electrode melting under vacuum, or VAR, is the refining process used for special-quality steels and stainless steels that are first made by conventional steelmaking methods and subsequently cast or forged into electrodes for vacuum drip melting into a water-cooled copper mold under very low pressures of 0.1 torr. Because of the high arc temperature and the small pool of liquid metal, sound ingots with dense crystal structure, low hydrogen and oxygen contents, and minimal chemical and nonmetallic segregation are produced. Direct current is employed for melting. The diameter of the electrode and its relationship to the crucible is critical and must be matched for the melting rate. Melting rates as high as 1150 kg/h (2500 lb/h) are used to produce ingots as large as 1.5 m (5 ft) in diameter.

Nonvacuum Refining

Secondary steelmaking processes used for special and clean steel production and carried out at atmospheric pressure without any supplemental reheating include argon bubbling processes such as capped argon bubbling (CAB), composition adjustment by sealed argon bubbling (CAS), argon-oxygen decarburization (AOD), ESR, and ladle injection methods. (Ladle injection methods are described in the sub-section "Secondary Steelmaking Equipment.")

Argon Bubbling Processes. Argon bubbling--argon stirring, trimming, and rinsing--is used for quick and uniform mixing of alloys, temperature homogenization, adjustment of chemical composition, and partial removal of nonmetallic inclusions. These functions are accomplished by either blowing argon through a refractory-protected lance lowered to within 300 mm (12 in.) of the ladle bottom or by blowing argon through porous refractory plugs inserted in the bottom or side wall of the ladle. Argon bubbling often supplements other secondary steelmaking operations by promoting bulk movement of steel in the ladle for chemical and thermal homogeneity, enhancing the flotation of inclusions, and promoting intimate metal-slag mixing for refining operations, such as desulfurization and deoxidation.

Argon stirring is the most vigorous of the bubbling treatments, injecting the highest flow rates of up to 0.3 m^3/min (10 scfm) through liquid steel. Stirring, which usually follows tapping, is used to mix the slag and metal and for temperature and chemical homogenization. The high flow rate breaks through the top synthetic slag layer and creates an opening for alloy and deoxidant additions. Sometimes radiant heat losses are promoted during stirring to prepare the heat for continuous casting. Carry over of slag from the converter should be minimized. Argon rinsing follows the stirring to help float the inclusions into the slag, and the gas flow rate is below 0.15 m^3/min (5 scfm). During argon rinsing, the gentle flow rate of argon prevents the formation of new heat-radiating surfaces. If the steel composition requires adjustment through ferroalloy additions, it is carried out during argon trimming which occurs between the stirring and rinsing steps. Just enough gas flow (0.15 to 0.3 m^3/min, or 5 to 10 scfm) during the trimming period allows the ferroalloys to mix in the steel and not become lost in the slag layer. The specified rates in this description are somewhat dependent on the ladle size.

The CAB and CAS methods for argon bubbling were developed to make controlled additions to the ladle as well as to improve the steel refining capability. The CAB process uses a conventional ladle with a cover and requires a synthetic slag over the steel surface after tapping (Fig. 15a) to act as a sponge for the absorption of nonmetallic inclusions. The introduction of argon into the covered ladle through a porous bottom plug stirs the metal vigorously and creates a slag-metal mix, unlike other argon bubbling methods, which require an intact slag layer to protect the melt from oxidation. The cap on the ladle prevents any air from affecting the metal. The slag-metal emulsion is useful in enhancing microcleanliness, chemical homogenization, desulfurization, and deoxidation. The CAS process (Fig. 15b) uses a refractory-lined snorkel, which is lowered inside the melt during argon stirring so the steel inside the snorkel is slag free. This allows the addition of ferroalloys and deoxidizers without any slag interference and, therefore, is an effective secondary steelmaking process for achieving compositional control.

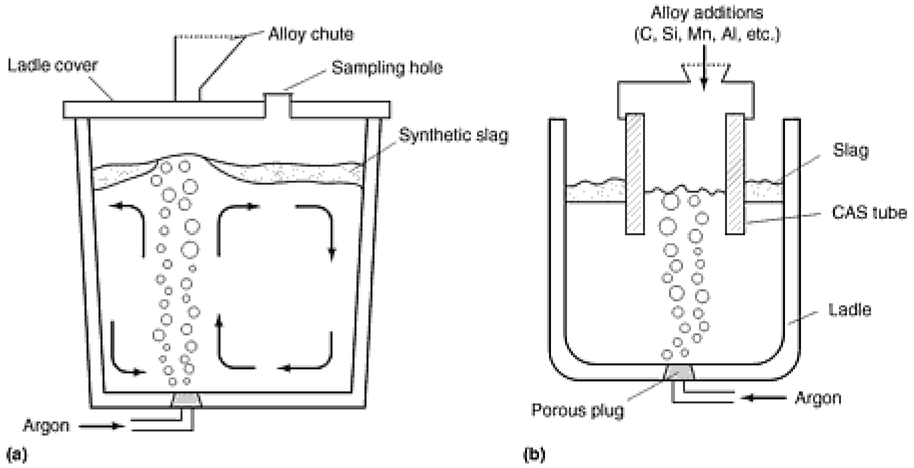

Fig. 15 Schematic arrangement of equipment used in argon-bubbling processes. (a) Capped argon bubbling (CAB) process. (b) Composition adjustment by sealed argon (CAS) bubbling process

The AOD process was designed for economical production of chromium-bearing stainless steels. A premelt is prepared in an electric-arc furnace by charging high-carbon ferrochrome, ferrosilicon, stainless steel scrap, burned lime, and fluorspar and melting the charge to the desired temperature. The heat is then tapped, deslagged, weighed, and transferred into an AOD vessel, which consists of a refractory-lined steel shell mounted on a tiltable trunnion ring (Fig. 16). As shown in Fig. 16, process gases (oxygen, argon, and nitrogen) are injected through submerged, side-mounted tuyeres. The primary aspect of the AOD process is the shift in the decarburization thermodynamics that is afforded by blowing with mixtures of oxygen and inert gas as opposed to pure oxygen.

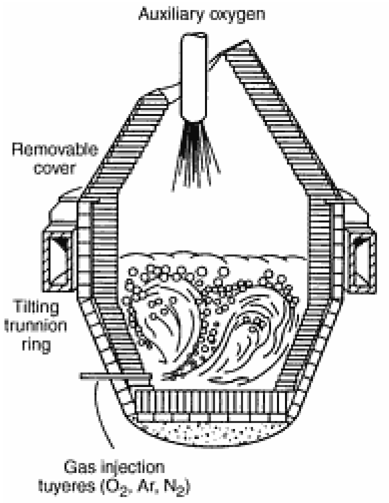

Fig. 16 Schematic of argon oxygen decarburization vessel

The heat is decarburized in the AOD vessel to 0.03% C in stages during which the inert gas to oxygen ratio of the blown gas increases from 1-to-3 to 3-to-1. During the blowing, fluxes are added to the furnace and a slag is prepared. Following the decarburization blow, ferrosilicon is added and the heat is argon stirred for a short period. The furnace is then turned down, a chemistry sample is taken, and the heat is deslagged. Additional alloying elements are added if adjustments are necessary, and the heat is tapped into a ladle and poured into ingot molds or a continuous casting machine. With the AOD process, steels with low hydrogen (<2 ppm) and nitrogen (<0.005%) can be produced with complete recovery of chromium.

The ESR process, like VAR, is a secondary refining process for electrode ingots of essentially the same composition as the finished product, except that ESR is carried out at normal atmospheric pressure and has a greater melting rate than VAR. Rotor forgings, rolls, molds and dies, nuclear containment vessels, and special casting shapes are produced by ESR. Alloy steels, stainless steels, and nickel-base superalloys are also commonly produced using ESR facilities. Electroslag remelting units consist of an open-bottom, water-cooled copper mold that contains the molten slag and metal, a high-current, low-voltage ac or dc power source, and an electrode feed mechanism. The mold rests on the starting plate at the beginning of melting and gradually moves upward as melting progresses (Fig. 17). Castings can be produced generally in any geometrical shape. The arc is struck between the base plate and the electrode to melt the slag, which is electrically conductive. As the electrode tip melts in the form of droplets and passes through the slag layer, some refining occurs. As melting proceeds, the molten pool of metal gradually solidifies. The rate is adjusted such that a molten pool depth equal to one-half the electrode diameter is maintained. The slag composition can be adjusted to serve as a desulfurizer or dephosphorizer as well as a reservoir for floating inclusions. Sulfur can be lowered to below 0.002%. The slag is comprised of fluorspar, lime, and alumina. The ESR process is ineffective in lowering hydrogen, however, as the process is essentially atmospheric. The ESR process is capable of using multiple electrodes, which can be melted into a single mold. The product surface quality is excellent and requires no conditioning.

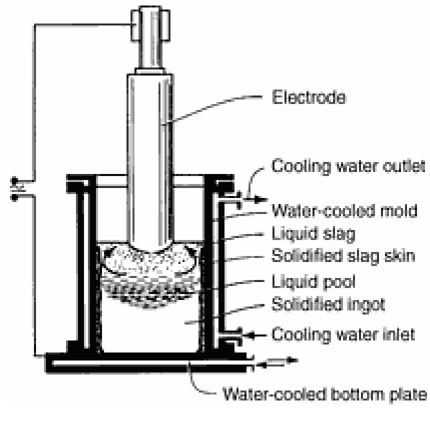

Fig. 17 Schematic of the electroslag remelting process

Reference cited in this section

35. W.T. Lankford, Jr., et al., Ed., *The Making, Shaping and Treating of Steel,* 10th ed., US Steel Publication, 1984, p 664-669

Casting

After making and refining by a selected combination of process steps described previously, the steel is then ready to be cast. The ladle containing the refined steel is equipped with either a stopper-rod arrangement or a slide-gate system to control the flow of steel during teeming into a series of molds or a continuous casting tundish. Pit-side practice is one of the key activities in steelmaking, which includes the final process steps before the steel is solidified by the ingot casting method. Therefore, the steel quality is significantly influenced by the pit-side practice adopted for a given steel grade. The ingots are stripped from the molds after the steel is almost completely solidified. Solid steel ingots are soaked in a heated pit where the temperature is homogenized for primary rolling into semifinished products of blooms, slabs, or billets. An attempt is made to reduce the "track-time" between stripping and inserting into soaking pits to conserve energy. Alternatively, a refined steel ladle can be directly teemed into a continuous casting tundish, which supplies molten steel for direct casting into semifinished or near-net shape steel cross sections.

Ingot Casting

An ideal ingot is characterized by a homogeneous chemical and physical structure with fine equiaxed crystals and with no chemical segregation and nonmetallic inclusions. However, depending on the nature of casting and solidification processes, ingots develop pipe, blowholes, chemical and nonmetallic segregation, internal fissures, and columnar crystal structure to varying extents. In addition, surface scabs and panel cracks also commonly develop on ingot surfaces. Ingot molds are usually tapered rectangular boxes of refractory-lined cast iron and are used in both orientations of "wide end up" or "wide end down." In the wide-end-down arrangement, molds may have an open top or a bottle top, whereas wide-end-up molds are generally equipped with open, closed, or plug bottoms. Casting of special high-quality steels presently employs wide-end-up configuration. The inner walls of the mold can be plain sided, cambered, corrugated, or fluted. Corrugating or fluting is done to minimize surface cracking of ingots during solidification by promoting a faster cooling rate and forming a thicker initial ingot skin. The liquid steel is fed into the mold either by top pouring or bottom pouring through refractory-lined feeders. The size and shape of an ingot is closely linked with the yield at the slabbing mill.

As the mold is being filled with steel, an ingot shell or skin forms next to the mold walls and bottom. This skin contracts as it cools to form an air gap between the mold wall and the solidified shell. Formation of an air gap reduces the rate of heat extraction from the ingot. As steel solidifies, the thermal gradient also becomes less steep and the rate of ingot skin formation slows down. The solubility of gases in molten steel decreases with decreasing temperature causing liberation of gases. Oxygen predominantly escapes as carbon monoxide after reacting with carbon. The amount of dissolved oxygen is decreased by the addition of deoxidizing agents. It is also dependent on the carbon level and chemical composition of the steel. The degree of deoxidation achieved during ingot solidification establishes four classes of steel: killed, semikilled, capped, and rimmed.

The rate of heat extraction from an ingot is affected by thickness, shape, and temperature of the mold, the amount of superheat in the liquid steel, the ingot cross section, and the type and chemical composition of the steel. Ingot size is selected to meet the product requirement and the capabilities of the hot-working facility. Ingots range from a few hundred kilograms in weight to as high as 300 metric tons for large forgings. An ideal cooling profile for a killed-steel ingot is shown in Fig. 18 as a function of time.

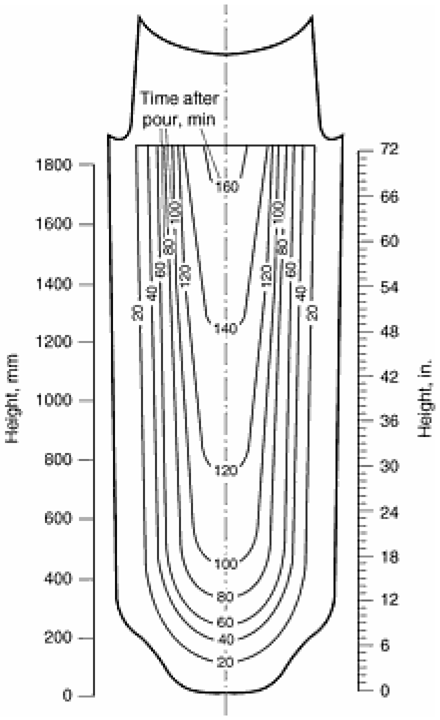

Fig. 18 Ideal solidification pattern of a hot-topped, wide-end-up ingot of fully killed steel

Deoxidation Practices. Because steel solidifies over a temperature range and as the carbon-oxygen chemical equilibrium is constantly changing with temperature, the carbon monoxide gas evolved from still liquid portions as a result of the new equilibrium condition may become trapped at solid-liquid interfaces to produce blowholes. The type of ingot structure is controlled by the degassing allowed during solidification. Figure 19 shows a series of ingot structures for a bottle-top mold casting, ranging from fully killed or dead-killed ingot (No. 1) to a violently rimmed ingot (No. 8) (Ref 36). The fully killed ingot, where no gas evolution is allowed due to full deoxidation through deoxidizer additions, is characterized by the intermittently bridged shrinkage cavity known as pipes. Fully killed steels are commonly cast in wide-end-up molds with hot tops to confine the pipe cavity near the hot top portion. Exothermic compounds are also used in killed ingot casting to allow flotation of nonmetallic inclusions and to keep the steel molten at the top. In a semikilled steel (No. 2), carbon monoxide is allowed to evolve slightly where the resulting blowholes compensate for the solidification shrinkage. The ferrostatic head helps keep the bottom half of the ingot free of blowholes, and the top begins to bulge due to the pressure exerted by the trapped gases. In ingot No. 3, more carbon monoxide is allowed to evolve resulting in greater volume of blowholes than required to compensate for the shrinkage. Some of the blowholes formed close to the side surface in the top half of the ingot are detrimental to the surface quality and lead to surface defects, known as seams, during subsequent hot working. The gas pressure punctures the initially frozen top surface and forces liquid steel up through the rupture causing bleeding. Excessive bleeding results in a spongy surface on products rolled from such ingots.

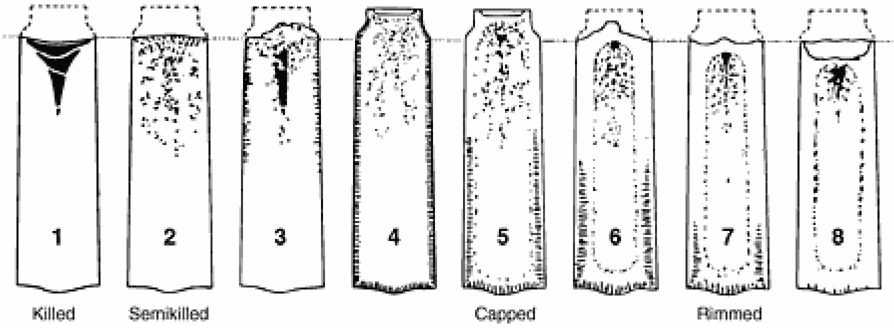

Fig. 19 Eight typical conditions of commercial steel ingots, cast in identical bottle-top molds, in relation to the

degree of suppression of gas evolution. The dotted line indicates the height to which the steel originally was poured in each ingot mold. Depending on the carbon and, more importantly, the oxygen content of the steel, the ingot structures range from that of a fully killed ingot (No. 1) to that of a violently rimmed ingot (No. 8).

Ingot No. 5 represents a typical capped ingot where numerous honeycomb blowholes extended from top to bottom as a result of strong gas evolution. This evolution causes the steel surface to rise after pouring, and a boiling action ensues, known as rimming action. This action is stopped by using a metal cap on the top of the mold. In this case, a thick, solid skin forms as blowholes are swept upward by the evolving gas. As the evolution slows down, honeycomb blowholes appear in the middle of the ingot. These blowholes do not pose any surface defect problems during rolling. Ingot No. 7 is a typical rimmed steel ingot structure where gas evolution is so strong that blowholes are confined to the lower quarter of the ingot only. The apparent increase in volume due to blowholes offsets the shrinkage that occur during solidification, thus, causing a rather flat-top ingot surface. A description of the production of different types of ingots, including the formation of blowholes and pipes that occur in ingots as a result of the chosen ingot casting practice, appears in greater details in Ref 37.

Major Casting Defects. Several other casting defects occur in steel ingots, such as segregation, inclusions, columnar structure growth, fissures, internal and surface cracks, and scabs. The type and size of ingot and the chemical composition of the steel primarily influence segregation in steel castings. The first metal to solidify very close to the mold wall, namely the chilled zone, has very similar chemical composition to that of the poured steel. However, as solidification proceeds at a decreasing rate, dendrite crystals of purer metal, which are low in carbon, manganese, silicon, sulfur, and phosphorus and other elements, solidify first. The dendrite crystals reject these elements into the remaining liquid. The last material to solidify contains the largest amount of these rejected elements. Segregation is commonly expressed as the departure from an average chemical composition in a bulk material. A positive or negative segregation refers to an increase or a decrease of an element from the average composition, respectively. Sulfur has the greatest tendency to segregate followed by phosphorus, cabon, silicon, and manganese. Larger ingots, which take a longer time to solidify, show greater segregation. When steel is stirred during solidification by convection currents, or turbulence due to gas evolution, the tendency to segregate is enhanced. Thus, a killed steel shows minimum segregation, whereas a rimmed steel shows a sharp boundary between the negatively segregated rimmed zone and a positively segregated core zone. In killed steels, however, "V" segregation occurs along the central axis of the ingot giving rise to axial porosity. Inverted "V" or "A" segregation occurs as a result of ingot disturbance during solidification and gives rise to a defect known as ingot pattern (Ref 38).

The chill zone, or the first formed layer of steel adjacent to the mold wall, has a small and randomly oriented crystal structure, followed by a large dendritic crystal growth characterized by a branching structure. Growth of the individual dendrites occurs principally along the longitudinal axes perpendicular to the ingot surface and can extend all the way to the center of the ingot. An ingot predominantly possessing these large elongated dendritic crystals is referred to as having a columnar structure. Such ingots tend to crack excessively if heavy reductions are taken during initial rolling passes. Usually, columnar structure gives way to the formation of large, equiaxed, randomly oriented dendritic crystal structure toward the center of the ingot. The relative proportion of columnar and equiaxed dendritic crystal structure depends on the steel composition, mold temperature, pouring temperature, and gas content of the steel. Movement of liquid steel during solidification is sometimes practiced by various mechanisms to decrease or eliminate the formation of columnar dendritic zone (Ref 39). This is achieved by the removal of all superheat in the liquid core, that is, to reduce the liquid core temperature to the steel liquidus temperature and by generation of nuclei fragments in the liquid core. Nuclei fragmentation is achieved by either remelting the columnar dendrite tip or by mechanical breaking. Long columnar crystals, especially in higher-alloy grades that resist plastic flow at hot-rolling temperatures, are undesirable because of poor cohesive strength (Ref 40).

Large internal bursts or fissures can be produced by the tensile stresses generated in the interior of the ingot by heating, cooling, or rolling process. If sufficient hot working is performed, these fissures can be completely welded if they do not extend to the surface.

Longitudinal as well as transverse cracks in the ingot wall can be seen on the surface of a cold ingot or during primary rolling. These ingot cracks are caused by excessively high pouring temperature. Weak interdendritic zones are formed that extend from the surface to the center of the ingot. A larger number of shorter dendrites develop if the pouring temperature is low. Transverse ingot cracking is also caused by discontinuities in the ingot wall arising from the surging molten metal in the mold. Improved mold design and use of mold coatings help the formation of folds due to a liquid surge. The occurrence of transverse cracking is lowered as carbon content increases in the steel. A hanger crack can be produced as a transverse crack when fins are formed over the edge of the mold. Corner design of the mold or the use of fluted molds give rise to longitudinal cracks. In general, these types of casting defects can be reduced by a proper mold and hot-top design. Molds cast in cement for ingot casting have also shown improved crack-free ingot surfaces.

Oxidized materials and sulfides, usually in combination, give rise to nonmetallic inclusions in the steel. These are deoxidation products in most cases, that were not removed during secondary steelmaking or during pouring. In some cases, these inclusions are added into the steel by the erosion of refractory linings used in ladles, furnaces, or molds.

In top-poured ingots, the pouring stream strikes the mold bottom and splashes against the lower mold walls. These splashes adhere and solidify forming a layer on the lower portion of the mold wall. As the liquid level rises, splashing diminishes. However, if the rate of rise for the molten pool is slow, the cooled splashed material oxidizes and attaches to the ingot surface as imperfectly bonded scabs. The thick scabs fold in by the rising steel level and, during rolling, give rise to seam or sliver type defects. In flat products, subsurface cracks occur parallel to these folds and produce surface laminations. A faster pouring rate can usually eliminate this kind of defect. Bottom-poured steels also do not have these cracks as the steel entering through the bottom in the mold does not splash and rises uniformly. Ingots can be scalped to remove major surface defects. The minor defects, however, are removed during the roughing (initial) passes as the scale is broken and removed during primary rolling.

Continuous Casting

The process of continuous production of semifinished shapes of blooms, billets, slabs, and rounds directly by solidification of refined liquid steel is termed continuous casting. The molten steel is fed into a steel reservoir called a tundish and transferred via nozzles into a continuous casting mold. Semifinished product yields as high as 95% can be realized in continuous casting as opposed to approximately 80% yield in the ingot casting/primary rolling route. Presently, 65 to 70% of finished steel is continuously cast worldwide. The combination of an electric-arc furnace and a small continuous billet, bloom, or slab caster, has lead to the formation of minimills characterized by their economic efficiency and simplicity. The first commercial billet and slab casters were installed in the early 1950s.

Steel quality is also improved by continuous casting because better control of steel cleanliness can be generally administered in the tundish and the mold and favorable solidification structures obtained through controlled cooling. High-quality clean steels are also produced through ingot casting, particularly the high-carbon, low-oxygen grades. For special grades, like bearing steels, ingot casting is the preferred route because primary rolling allows a larger reduction ratio through hot working and, therefore, a more sound internal structure. A 30 to 1 reduction ratio is required as a minimum for certain bearing grades, which is not achievable from continuously cast billets, or even blooms, if large bearings are to be manufactured.

The yield improvement in continuous casting over ingot casting is primarily due to the elimination of scrap generation in three areas: primary rolling mill, steel pouring practice, and soaking-pit ingot heating. In addition, short ingots, ingot butts, and general pit scrap lower the ingot casting yield. Cropping of top and bottom parts in an ingot due to piping or high inclusion level is always associated with ingot casting. Conversely, it can be easily understood that the longer a continuous caster operates without an interruption (number of heats continuously processed), the higher is the yield for any given casting size and number of strands on a caster.

Quality improvement ensues from the fact that there is less variability in chemical composition and better solidification characteristics. Segregation is minimized, both vertically along the length of the billet or bloom and across the cross section. Inclusion levels, however, could be higher in continuously cast steels, particularly in transition zones (material cast during change of heats), and as a result are detrimental to bearing-grade steels, as discussed earlier. Further down the line, surface dressing requirements prior to finish rolling are also reduced as surface defects (seams, scabs, etc.) on a continuously cast product are less than a primary rolled product from ingots. This also improves the yield. In general, fewer internal and surface defects are present in continuously cast material.

Elimination of soaking and primary rolling steps considerably improves the energy efficiency of continuously cast product. Higher yield in continuous casting lowers the energy consumption per ton of steel processed. With the advent of hot charging of semifinished products from a caster into reheating furnaces prior to finish rolling, energy efficiency of continuous casting has been greatly enhanced. Soaking pits for ingot reheating burn fuel and are a source of pollution. Lower capital and operating costs are required in continuous casting by eliminating ingot processing steps and by yielding higher throughputs (Ref 41).

Process Description. Figure 20(a) shows the main components of a continuous caster. A casting machine essentially consists of a liquid-metal reservoir and a delivery system, known as a tundish, a water-cooled mold, a secondary cooling zone with a containment section, bending and straightening rolls, shearing equipment, and a cooling bed or run out table. A caster can have several strands (number of liquid streams tapped from the same tundish), each equipped with a mold, secondary cooling and containment arrangement, shearing station, etc. The number of strands used is a function of the heat size and the shape being cast.

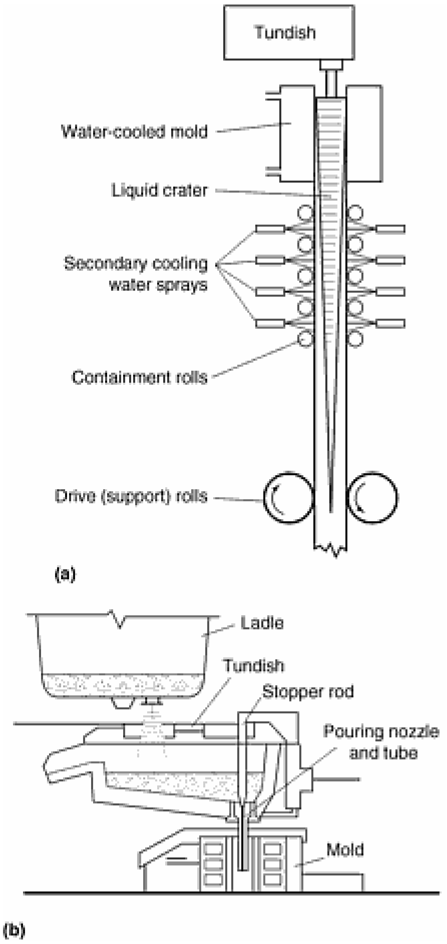

Fig. 20 Continuous casting. (a) Major components of a continuous casting machine. (b) Liquid metal flow from the ladle into the tundish and from the tundish into the mold

The casting process begins with the bottom end of the mold plugged with a dummy bar connected to an external mechanical withdrawal system. The tundish is filled to a certain height at a controlled rate by refined molten steel poured from ladles. The liquid steel flows from the tundish through nozzles and into the mold (Fig. 20b). When the steel level reaches a certain height in the mold, the dummy bar is withdrawn at a predetermined casting speed. Casting speed is dependent on the machine characteristics, such as cast section, cooling efficiency, metal feed rate from the tundish, and the desired cast structure. When the dummy bar head, which is now attached to the solidified shape being cast, reaches a certain position in the withdrawal station, it is mechanically disconnected and the dummy bar removed. The solidified casting continues through the withdrawal system to the shearing station.

Solidification begins in the water-cooled mold just below the liquid steel meniscus where a shell is formed in contact with the mold wall. The distance between the meniscus level and the point of complete solidification is known as the metallurgical length of the caster. The mold is vertically oscillated to prevent sticking of the solidified shell to the mold wall. In addition, molds are tapered to ensure that the solidified shell is in contact with the mold wall for better cooling efficiency. Friction between the mold wall and the solid shell is minimized by using mold compounds or lubricants, such as oil or fluxes that form a fluid slag. Casting conditions are established to ensure that the steel shell is thick and strong enough to withstand the ferrostatic pressure of molten steel in the mold after it leaves the mold. The material is fully solid before it reaches the cutter and in many cases, it is solid before it arrives at the straighteners. Further heat removal occurs in the secondary cooling zone for complete solidification. Water and/or mist spray cooling is employed in this zone to maintain optimum cooling rates and strand surface temperatures. Support rolls guide the strand as well as prevent sectional bulging due to internal ferrostatic pressure from the molten pool at the strand core. Cooling sections are designed to minimize internal and external flaws or defects. After the secondary cooling, bending and straightening are performed before shearing into the desired length for further processing, either in hot or cold condition. Some of the casters can be used to cast more than one shape by changing the mold (Ref 42).

Capital cost of installation has been lowered over the years while improving the quality of the cast product by progressively reducing the height of the machine. Older installations are vertical machines with a straight mold and cut off in the vertical position whereas newer installations use a bow-type machine with curved mold and progressive straightening. New slab casters are usually bow type because slabs are not self supporting in the secondary cooling zone, whereas billets or blooms are self supporting and, therefore, can be cast on a vertical machine. Generally, the shape of the cast material, productivity and quality of the product, and the cost determine the type of machine chosen.

Design Features in Continuous Casting for Quality

Temperature control is more critical in continuous casting than in ingot pouring. Enough superheat must be maintained to allow the molten steel ladle travel from tapping to teeming stations and to prevent freezing at the tundish nozzles. At the same time too much superheat can cause insufficient solidification in the mold and thus a breakout after leaving the mold. Low superheat casts provide better uniform cast structures with a wider equiaxed crystal zone than high superheat casts. Homogenization of temperature is, therefore, practiced either by argon bubbling through a porous bottom plug or by lancing from the top in the ladle before the steel is teemed into a tundish.

Continuously cast steels must be fully killed (deoxidized) to prevent blowholes or pinholes from forming close to the surface of the cast product, which result in seams upon subsequent rolling. Full deoxidation is achieved primarily by silicon deoxidation for coarse-grain steels and by aluminum deoxidation for fine-grain steels. Aluminum-killed steels, however, can cause problems at the tundish nozzle by clogging them with alumina deposits. High-quality products commonly use a ladle refining practice prior to casting and take special measures for preventing nozzle blockage.

Liquid steel is fed continuously or semicontinuously from the ladle to the tundish and is distributed to individual molds through nozzles in a continuous stream (Fig. 20b). Stopper rod or hydraulically or electrically controlled slide-gate systems are used to transfer steel from the ladle to the tundish.

Role of the Tundish. Tundishes have nozzles located at the bottom, which serve primarily as a metal distributor to the mold. Metal flow patterns are very critical to the product quality. Flow-control devices, such as refractory dams and weirs, are attached to the tundish to distribute the metal flow, to minimize turbulence, and to eliminate dead flow zones (Ref 43). These devices enhance the stability of the metal streams entering the casting mold. Significant cold modeling work has preceded the design of optimal configuration of these flow-control devices. Metal is poured as far away as possible from the nozzle location directly on a wear resistant pad. A constant metal height above the tundish nozzle is required to discharge the metal at a constant rate and, in turn, to maintain constant casting speeds. Tundishes also perform the function of a metal reservoir which allows unabated casting during ladle change overs for sequence casting of heats. It is imperative that the ladle change be done in the shortest possible time.

The metallurgical role of a tundish is to facilitate separation of inclusions and slag from entering the mold. The metal residence time in the tundish is a key parameter in meeting this condition. Tundishes are preheated prior to metal pouring and are often covered to minimize radiation heat losses. Tundish nozzles are either a metering (or open) nozzle or a stopper-rod nozzle. Metering nozzles essentially control the metal discharge rate by the bore of the nozzle and the ferrostatic pressure (metal height in the tundish) above the nozzle. They are commonly used for silicon-killed billet or bloom castings. Stopper-rod nozzles are used for slab casting of aluminum-killed steel, and the flow is monitored by raising or lowering the rod above the nozzle opening. Alumina buildup and clogging is compensated by raising the rod if other means of preventing buildup are not in place. Inclusion levels in the metal rise, particularly during ladle change overs. The time available for floating inclusions is much shorter in continuous casting than in ingot casting. However, nozzle clogging is prevented by bubbling argon through the stopper head and nozzle units in modern installations. Slide-gate systems additionally provide the capability for changing nozzles during casting as well as changing nozzle size.

Shrouding. Stringent surface and cleanliness requirements placed on special-quality steels have necessitated the use of closed stream or shrouded castings. Open-stream castings pick up oxygen- and nitrogen-forming inclusions, which have deleterious effects on steel properties, as described earlier. Ladle-to-tundish and tundish-to-mold shrouding are commonly employed to protect the steel from air, particularly the aluminum-killed grades, which have a potential of forming alumina inclusions. Inert-gas shrouding and refractory-tube shrouding are the general types of methods used. Refractory-tube shrouds are made of fused silica or alumina graphite. Figure 21 shows an example of a ladle-to-tundish and tundish-to-mold refractory-tube shrouding system.

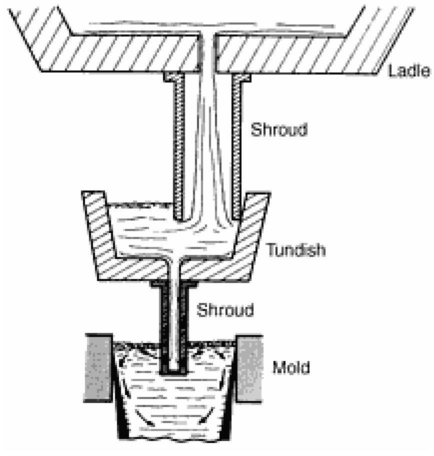

Fig. 21 Schematic of a refractory-tube shrouding system for minimizing oxidation during pouring

Mold Characteristics. The mold serves the function of partly solidifying the steel to such an extent that the shell thickness and shape, temperature distribution, and surface and internal structures are appropriate after exiting. Molds are open-ended boxes that contain an inner lining made of a copper alloy and are externally supported by a steel structure. Cooling water flows between the liner and the outer steel structure to extract heat from the solidifying steel in contact with the copper liner. Molds are either tubular or plate type. One-piece tubular thin copper linings are used for smaller billet and bloom casters. Plate molds consist of a four-piece copper lining attached to steel plates. In some designs, opposite plates can be adjusted to cast different rectangular slab shapes and, therefore, are more adaptable. Plate molds also allow the change of taper to accommodate different shrinkage characteristics of different steel grades. Silver-alloyed copper is used for high-temperature strength. The inside liner surface is often nickel or chrome plated to provide a harder working surface and to avoid copper contamination of the cast strand surface. Thermal and mechanical strains cause a distortion of the mold and thus affect product quality. Thermal strain distortions, which are highest at the meniscus level where the steel temperature is highest in the mold, cause permanent distortion due to lower yield strength of copper. Mold wear at the exit end also causes reverse taper phenomenon (Ref 44).

Heat Transfer in Continuous Casting

Heat transfer conditions in the mold have been thoroughly investigated through modeling and plant verification (Ref 45). The predominant transverse heat transfer can be considered as a flow of heat energy through a series of thermal resistances from the liquid steel at the core and the water sink of the cooling system. Heat transfers (a) in the solidifying casting, (b) from the steel shell surface to inner copper lining, (c) through the copper lining and (d) from the outer copper lining to the mold-cooling water. Sensible heat changes (the heat absorbed or evolved by a substance during a change of temperature that is not accomplished by a change of state) in the steel strand due to lowering of temperature and latent heat release due to phase changes comprise the heat to be transferred in the solidifying casting. In addition, a mushy zone exists between the liquid and the solid shell, the thickness of which is dependent on the steel carbon level. Also, the thickness of the solid shell changes continuously from the meniscus to the bottom of the mold, and transfer through this shell is by conduction. Transfer of heat from the steel shell to the mold wall is complex and occurs by radiation as well as conduction due to the tendency of the formation of an air gap between the mold and the shrinking cast shell. A large air gap, which can form longitudinally as well as in transverse direction, represents the slowest of the heat transfer steps and therefore, controls the overall rate of heat transfer. While bulging due to internal ferrostatic pressure tries to reduce the air gap, an increase in shell thickness away from the meniscus tends to resist bulging. Thus, the formation of the air gap is a dynamic phenomenon. Because mold taper is intended to reduce the air gap, it enhances heat transfer. At the inner copper wall, heat transfer is also affected by the quantity and type of mold flux and lubricant used. Fluxes and oil that wet copper assist in heat transfer. In general, the local heat flux down the mold length is maximum just below the meniscus and gradually decreases down the mold length. The average heat flux for the entire mold increases with increasing casting speed. Heat transfer through the lining is essentially by conduction and is dependent on the copper conductivity and thickness, whereas the transfer through the cooling water is by forced convection. Water flow rate and pressure control the heat transferred through it. Typically, higher cold-face temperatures are encountered in billet casters due to the lower thickness of the copper lining than is the case with slab casters. Water flow must be uniform through the passages of the mold with an adequate volume, temperature, pressure, and quality. Usually water flows vertically upward in the mold. Optimum water pressure is required to suppress boiling and to prevent mechanical mold deformation. Water quality is important because scale buildup on the copper lining can be detrimental to heat transfer and copper strength. Use of baffles and headers in the water flow region is critical in maintaining a proper velocity. The difference between the water inlet and outlet temperatures, ΔT, is a good indication of the mold cooling efficiency where high, low, or unequal mold face values indicate a low water flow rate, scale buildup, and an unsymmetrical pouring stream, respectively. Unequal temperature differences on two faces could also mean a strand misalignment.

Mold Oscillation and Lubrication. To minimize the risk of breakouts (in which liquid steel breaks through the thin solidified shell inside or just outside the mold) and mold-strand adhesion, the mold is lubricated and oscillated. Various hydraulic or mechanical actuators are used to reciprocate the mold. Sticking of the strand to the mold can be exacerbated by local rough areas in the mold or by the buildup of tensile forces on the skin. Generally, a negative strip is applied where the mold moves faster than the casting speed, which results in a compressive stress on the solid shell allowing closure of surface fissures and porosity. The upstroke is taken rapidly, and the mold is returned to the starting position quickly.

Both liquid and solid types of mold lubricants are used. Semirefined mineral or vegetable oils are used to form a film along the mold walls when casting silicon-killed billets or blooms. Solid mold fluxes or powders are used with submerged refractory tubes when casting slabs or blooms of aluminum-killed steels. These solid lubricants also help in heat transfer at the strand-mold interface and provide thermal insulation and reoxidation protection to the liquid steel at the meniscus. Mold fluxes also assist in absorbing nonmetallic inclusions. Mold fluxes melt and attain optimal fluidity when they come in contact with the molten steel. Solid mold fluxes are SiO_2-CaO-Al_2O_3-Na_2O-CaF_2-based with small additions of carbon. Iron oxide is avoided to prevent reoxidation. Fluxes are either fly-ash based or synthetically produced as frits or granulated powder.

Cooling Characteristics. Secondary cooling, strand containment, and a withdrawal mechanism form an integrated system, particularly in modern slab casters. The metal is control cooled through a secondary cooling zone while being supported and withdrawn by several sets of rolls to the cutoff table after leaving the mold. Secondary cooling is subdivided into a series of zones positioned through openings between the containment rolls. For more uniform cooling, water-mist sprays have replaced the conventional water-spray cooling in newer installations (Ref 46). At the desired casting speed for a grade of steel, secondary cooling is required to provide adequate water for complete solidification and to regulate the thermal gradients in the strand and the strand surface temperature. Secondary cooling also helps cool the containment rolls. Improper thermal gradients cause internal and surface cracks and shape distortion. Over or under cooling causes thermal strains and could exceed the low ductile strength of the shell at high temperatures. Improper cooling can also result in reheating of the shell by the liquid core heat. A smooth transition from the spray cooling to radiation cooling is desired to prevent reheating. A recirculating water system is used and the water flux (the amount of water per unit area of surface contact) is distributed through properly spaced nozzles along the zone. Changes in the water flux can be compensated for changes in the casting conditions.

Strand Movement. The strand is supported and guided from the mold exit to the cut-off position and is driven at a controlled speed by a series of retaining rolls extending across its two opposite faces in a horizontal direction. Containment can be further enhanced by edge rolls placed across the other two faces perpendicular to the casting direction. Mechanical stress and strain incurred during processing are minimized by containment. The strand is supported on all four faces below the mold and on two faces in the lower levels. The tendency to bulge is greatest just below the mold where the shell thickness is low and the internal ferrostatic pressure is high. Also, the roll spacing is shorter near the mold than away from it. In addition to containing the strand, the series of rolls placed along the prescribed arc to transition and guide the strand from vertical to horizontal have to be strong enough to withstand the bending reaction forces. Triple-point bending or bending through three arcs with progressively smaller radii is practiced in modern casters to ensure improved surface quality because sharp bends can crack the surface due to excessive tensile stresses generated during bending on the outer surface. Following bending, the strand goes through a multiroll straightener, which unbends the strand and reverses the tensile and compressive forces in the horizontal faces. In most continuous-casting machines used currently, curved molds, which do not require bending, are used. The strand goes immediately through straightening rolls.

Withdrawal of the strand is achieved by drive rolls placed in the vertical, curved, and horizontal sections of the machine. These rolls tend to impart compressive forces in the surface of the strand, resulting in better surface quality. Thus, the objective is to "push" the strand through the casting machine rather than "pull" the strand, which can produce tensile stresses and attendent surface defects. Drive rolls are, therefore, placed before the bending rolls, where possible, to offset tensile stresses. The required traction to drive the strand is distributed over the multiple sets of drive rolls used. To prevent shape deformation, excessive force by the drive rolls to grip the strand must be avoided. The strand subsequently moves to the cut-off section where smaller sections are mechanically sheared, and larger sections are torch cut.

Productivity and Quality

Since the commercial inception of continuous casting in the early 1960s, tremendous gains in productivity have been achieved through several measures. Machine downtimes have been reduced by (a) lowering machine set-up time between casts, (b) reducing mold change times, (c) reducing the number of stoppages due to strand breakouts, nozzle blockage, and uncontrolled metal flow, (d) minimizing occurrences of out-of-specification heat composition and temperature, and (e) cutting down machine maintenance needs. In addition to improved steelmaking practices and better caster design, the advent of sequence casting, slab slitting with oxyfuel torches to reduce the frequency of mold changes and reduce mold inventory, variable-width adjustable molds, split molds, top-fed dummy bars, and hot charging for direct rolling have improved the productivity substantially. It should be realized that hot charging implies the need for hot-surface preparation and inspection steps, and calls for excellent control of surface finish by the caster itself.

The quality of continuously cast product is dependent on the steelmaking and casting practices. Surface defects include deformed cross sections; longitudinal and transverse cracks; laps, scale, and trapped inclusions; and mold oscillation marks. Subsurface pinholes, blowholes, inclusions, and cracks also appear, whereas porosity, inclusions, segregation, and cracks are internal defects. Specific techniques are employed to minimize these defects. External cracks are usually reduced by proper mold and secondary cooling at controlled casting speed, mold lubrication, mold coatings, mold wear control, and machine alignment. Internal cracks and porosity can be minimized by machine alignment, electromagnetic stirring, in-line reductions, multipoint straightening, compression casting, and control of temperature and casting speed.

The lack of integrity of the pouring stream between the tundish and the mold and improper casting speed give rise to laps and scabs. Oscillation marks generally originate from the type of mold oscillation adopted. Proper deoxidation and stream shrouding can eliminate blowholes and pinholes, while segregation is minimized by electromagnetic stirring, control of superheat, and casting speed. Inclusions are avoided by improved steelmaking, deoxidation, and shrouding practices. The desire to roll flat products, which do not require prior surface conditioning, has driven the recent developments in "clean" steel manufacturing, electromagnetic stirring, and mist cooling at the secondary zone. The incidence of surface cracks has been dramatically reduced by these three developments.

Clean steel technology involves minimizing the formation of inclusions during deoxidation or reoxidation, lowering pickup from refractories, and enhancing inclusion separation and removal prior to casting. Control of sulfide and oxide inclusion morphologies are also critical. These controls are brought about through a variety of process steps, such as slag-free tapping, ladle metallurgy, shrouding all open liquid-metal streams, proper refractory selection, proper tundish design, use of mold powders, and electromagnetic stirring.

Electromagnetic Stirring (EMS). Stirring of the liquid steel during solidification using a magnetic field has resulted in sound internal quality (reduced segregation, cracking, and porosity), subsurface cleanliness through a modified flow pattern, reduced criticality of casting parameters (temperature and casting speed), and increased productivity through higher casting speeds. Initial applications of EMS on billet casters clearly showed a decreased columnar zone and a wider equiaxed crystal zone resulting in lower center-line segregation. In a rotary EMS system installed in the mold, a rotating magnetic field imparts a circular motion to the liquid steel. The flow breaks the dendrite tips and provides nucleation sites for equiaxed crystal growth while producing a solid skin by moving the lighter inclusions to the center of the billet. Linear EMS systems are placed below the mold generating a vertical circulation pattern. Inclusions are uniformly distributed while more equiaxed crystals form by a similar mechanism as that obtained by the rotary stirrer. In slab casters, EMS is additionally used to break the flow pattern of the incoming stream of metal into the mold, thus reducing the penetration of the stream into the liquid pool (Ref 47).

Mist Cooling. Conventional water sprays in the secondary cooling zone can aggravate the occurrence of surface cracks because cooling is uneven in both the longitudinal and transverse directions. Local overcooling can also occur due to trapping of water in different sections. The formation of steam bubbles and vapor film interferes with the heat transfer. An air-water mist provides improved cooling characteristics due to better heat transfer, removal of steam by the compressed air, and lesser use of water volume. Edge-to-edge temperature variations are less, and water trapping at containment and drive rolls are eliminated. The air-water mist is created by an atomized nozzle in which cooling water and air are premixed and discharged under pressure (Ref 46).

Special Continuous Casting Processes

Besides the conventional methods of casting billets, slabs, blooms, and rounds in vertical machines for which a large number of installations are commercially available worldwide, alternative processes have been developed to reduce the capital cost, to improve the product quality, and to cast smaller section sizes. These include horizontal casting, rotary continuous casting, and strip casting. These processes are described in greater detail in Ref 48.

Horizontal casters require lower capital investment and smaller space. The cast sections inherently have low ferrostatic pressure resulting in less strand bulging and the absence of straightening and bending lowers stresses, which allow casting of crack-sensitive grades. The absence of tundish-to-mold reoxidation is also helpful. In rotary continuous casting, the strand and mold are rotated, which results in the development of centrifugal forces providing intimate contact between the mold wall and the steel. This results in high heat extraction rates during the initial stages of solidification.

In strip casting, strips are directly cast from liquid steel rather than by rolling of strip bars in hot strip mills. Significant cost savings can be realized by eliminating strip bar reheating and hot strip mills and by improving upon the yields of a conventional strip production route. Strip thicknesses of less than 1 mm (0.04 in.) can now be directly cast.

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Hot Rolling

All of the inherent quality aspects of steel that relate to cleanliness are derived during secondary refining and casting. Subsequent practices of primary and finish rolling are essentially the art and science of controlling the product microstructure and properties. Specialties in rolling practices pertain to a precise control of the amount of cross-sectional reduction taken at, or within, a certain temperature range and the associated cooling profile of the product. Many forms of steel products require subsequent heat treatment for achieving the desired microstructure because the as-rolled microstructure is not adequate. Other practices of hot working, such as forging or pressing, are described elsewhere in this Handbook. In addition to hot working, several final products need cold working, particularly in flat or circular form, to achieve strength and/or texturing. Product forms such as strips and wires require an additional step of coiling at a fixed temperature, because cooling profiles in the coiled condition determine the final microstructure attained. Between the primary and finish rolling steps in hot working, the semifinished steels require a surface preparation, known as conditioning, particularly if they are rolled from ingots.

Primary Rolling

Primary rolling pertains to initial breakdown rolling of ingots to produce semifinished shapes of blooms, billets, slabs, and rounds. If the steel is continuously cast, these shapes are directly formed by the shape of the mold. There is no clear distinction between these shapes as some overlap exists. Billets and blooms tend to be square, while slabs are oblong. Blooms are larger in cross section than billets. Further subdivision of shapes is made on the basis of the final product shape, such as tube rounds, plate slabs, strip bars, etc. Generally, a square cross section of 125 × 125 mm (5 × 5 in.) is used to distinguish a billet from a bloom. The length of these shapes depends on the starting ingot size and the finished product size as well as the mill capability (Ref 49).

Ingot cross section is first reduced to a square, oblong, round, or other convenient shape with rounded corners. During this operation the length of the ingot increases as the cross section is reduced. The ends are cropped, and the rolled piece is split into desired lengths for further rolling. Rolling of ingots directly into products is often desired as intermediate reheating is eliminated. However, such a practice is more suited for large cross-section finished products, such as wide flange beams and rails. Primary rolling mills are described by the center-to-center spacing of the work rolls. Usually, primary mills are multiple-stand mills and the size description relates to the first stand. The function of all primary mills is fundamentally that of cross-sectional reduction and cutting into desired lengths and weights, which is achieved by passing the stock through a series of rolling stands. Crops and mill scale are useful by products of the primary mill and are recycled to the steelmaking converter.

A series of thermal and mechanical operations are carried out during primary rolling. Reheating and homogenization of the ingot temperature is achieved in soaking pits (Ref 50). This temperature is optimized to maintain sufficient plasticity in the steel during rolling while minimizing overheating in the pit. Initial passes, known as break-down or roughing passes, break up the coarse crystalline structure of the ingot into a refined structure by heavy rolling pressure and recrystallization during hot working. Scales formed in the soaking pit are dislodged as soon as the ingot enters the first set of rolls. This is essential to prevent the scales from embedding into the surface. Solidification voids from ingot casting are welded shut. Further cross-sectional reduction of the steel occurs as the rolled piece passes through subsequent stands. Physically (fishtails) and chemically (high inclusion) unsuited ends are cropped. The semifinished product is then cut to desired length and weight and is left to cool if further rolling is not immediate.

Primary Mill Types. In most primary mills, a roll stand is required to impart more than one reduction. In this case, the mill roll-out stage must have facilities, that is, manipulators, to turn the rolled piece, and the rolls should be reversing. If the rolls are not reversing, as is the case in some older installations, there are mechanisms to return the steel to the rolling entry side, either by passing over or under the rolls. Positioning of rolls to produce the desired cross section is simultaneously done. The basic operation in a primary slabbing or blooming mill is the gradual compression of the steel ingot between the surfaces of two rotating rolls. The physical properties of the ingot prohibit the entire reduction being accomplished in one pass. Therefore, the ingot must be rolled using a sequence of passes designed on the basis of mill capacity and capability.

Common types of primary mills include two-high reversing mills, two-high tandem mills, three-high mills, three-high billet mills, cross-country billet mills, and various combinations. Two-high reversing mills are most versatile in their capability to roll different sizes of ingot. (As the name implies, a two-high stand consists of two rolls, one above the other.) The rotation of the rolls can also be reversed. Reductions are accomplished in both directions of roll rotation. These mills are associated with low production rate. Therefore, combinations of different types of mills are used to improve the productivity, such as different size two-high mills arranged in tandem. High-lift blooming mills and slabbing mills are other variations of a two-high reversing mill that provide special rolling capabilities (Ref 50). The two-high tandem mills consist of several single stands of paired rolls, spaced such that the rolled piece is free between the stands. Normally the piece is rolled in one pass in each stand. Each stand is designed for ideal draft, and no time is lost in reversing the roll direction. These mills are limited by the size of ingot that can be rolled and are expensive to build. Two-high tandem mills are usually used for roughing the ingot for final rolling in a slab or billet mill. In three-high mills, the top and bottom rolls rotate in the same directions while the middle roll rotates in the opposite direction. Rolling reductions are alternately taken between the top and middle roll in one direction and between the middle and bottom roll in the opposite direction. An elevating table is required to position the steel piece between the appropriate sets of rolls during rolling. These mills have a constant speed of rotation, thus initial passes are too fast and the last passes are too slow. The design of roll passes and the operating units in a primary mill are described in Ref 50.

As large size ingots are produced now for greater productivity, direct rolling of billets in the primary mill has become difficult for smaller cross-section billets. Thus, a blooming mill is followed by a billet and bar mill, which rolls the blooms into smaller cross sections, usually without a reheating step. Reheating facilities are required if the rolling temperature range is narrow for special grades of steel. Three-high billet mills operate using the same principles as the three-high blooming mill. Different parts of the rolls in the horizontal direction are used to make successive reductions in cross section through grooves along the roll length. Several sizes of billets can be produced by a single three-high billet mill. Cross-country billet mills are comprised of several stands of rolls, so arranged that the piece to be rolled is never in more than one stand at the same time. The stands can be placed side by side, and the piece is moved along the roll tables by manipulators and guides. The direction of rolling is reversed on the adjacent table after rolling through one or more stands. The roll stands along the adjacent side table are normally rotated in the reverse direction. The speed can be controlled for each stand independently, and faster rolling speeds can be used for finishing passes. In a continuous billet mill, stands are in series one after the other. The bloom enters the first stand and exits the last, taking only one pass in each stand. The rolling speed of each subsequent stand is adjusted to account for the increased length of the piece from the previous stand. Some of the stands in these mills may be vertical or could simply use vertical edgers. These mills have high output as scrap losses are low.

The product from the blooming mill is cropped by bloom-crop shears to discard the hot top (pipe) before entering the billet mill. Stationary shears are used to cut the large cross-section billets to size, whereas flying shears are used to cut smaller cross sections as the billets travel in a continuous operation.

Conditioning of Semifinished Products

Ingot defects described in the sub-section "Major Casting Defects" and some additional defects arising during heating and rolling are carried through primary rolling, and they appear on the surface of the semifinished product. These defects require removal before finish rolling is performed. Figure 22 shows the surface defects that originate from ingot defects or during heating and rolling. A cinder patch defect refers to the scabby bottom of the ingot where material is picked up from the soaking-pit bottom. The ingot is placed in the pit so the cinder patch is confined to the hot-top end of the ingot, which is discarded after rolling. Burning of ingots due to direct impingement of flames on the ingot corners during soaking make the steel nonsalvageable, as tearing or rupturing occurs during primary rolling. When fins or projections produced by one pass are bent over and rolled during subsequent passes, laps appear on the semifinished product surface. Deep laps are difficult to repair. Several nondestructive methods are employed to inspect the material and to determine the conditioning requirements. Often all the defects do not have to be removed depending on the application or the steel grade being processed. Milling and chipping machines are used to remove the surface imperfections on blooms or slabs. Scarfing in the steel mill consists of surface removal by the use of oxygen torches. The oxygen rapidly oxidizes the steel surface generating elevated temperatures that cause the oxidized product to become liquid. Scarfing can be carried out manually or mechanically. Grinding is also commonly used to remove surface defects.

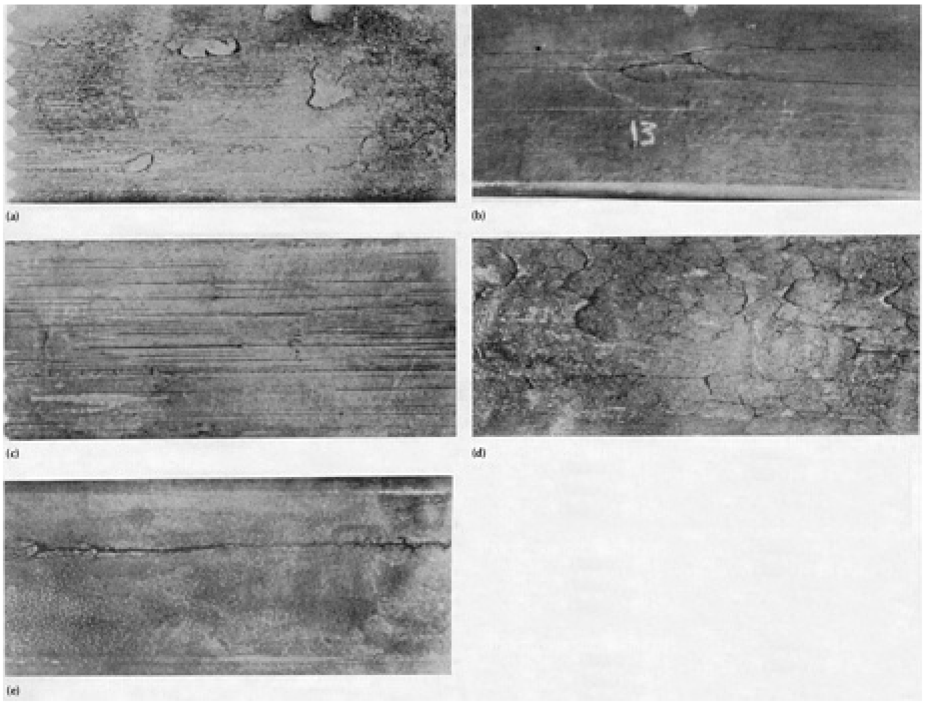

Fig. 22 Surface defects on semifinished products made by primary rolling of ingots. (a) Scabby surface of a bloom. (b) Deep seam originating with an ingot crack. (c) Clustered seams. (d) Burned steel bloom. (e) Lap on a rolled steel product

Semifinished products are rolled at temperatures well above the critical temperature range of the steel and thus, during cooling after rolling, must pass through transformation range. Depending on the size and chemical composition of the steel grade rolled, it might be necessary to control the cooling rate of the semifinished product to discourage the formation of flakes or small internal ruptures and to minimize the generation of internal thermal stresses. Flakes normally occur some distance away from the end of a rolled piece and often midway from the surface at the center of the section. Flakes are generally attributed to the dissolved hydrogen in molten steel and proper retardation of cooling from the rolling temperature is effective in prevention of flaking. Before the advent of controlled-cooling practices, steels were buried in sand or ashes (insulators) to retard the cooling process, which helped minimize the development of internal stress and lowered the hardness. Newer controlled-cooling processes involve automatically controlled furnaces, which can slow cool the steel at desired cycle times through predetermined temperature ranges. Cooling cycles are shorter when using controlled cooling as rapid cooling and holding at desired temperatures have become possible. When the steel is out of the thermally sensitive range, steels can be air cooled. These cooling profiles can be determined by judicious use of isothermal transformation diagrams specific to the grade of steel (Ref 51). In general, the higher holding temperatures followed by air cooling can be used for the carbon and lower alloy steels, and lower holding temperatures followed by reheating to temperatures just below the critical temperature range can be applied to high-alloy deep-hardening grades of steel.

Finish Rolling

After an ingot is converted into a semifinished shape (bloom, billet, slab, or a round), it is ready to join the products made by continuous casting. The process steps of conditioning and controlled cooling are more applicable to ingot products, because controlled cooling is adopted in continuous casting during solidification if the product is not finish rolled directly. Also, surface defects in continuously cast products are minimal. Beyond this point, steel is plastically worked, either hot, cold, or both, to attain the desired finished shapes. Rolling is followed by heat treatment, if required, to obtain the desired microstructure. Separate rolling mills are used to obtain the final regular shapes of plates, sheets, strips, rounds, bars, tubes, wires, and rods and medium-to-heavy sections for wheels, axles, rails, beams, channels, and angles. Other special mills are used to forge, press, or roll nonconventional sections. These mills vary in capacity, layout, and design worldwide. The function of finish rolling is to permanently deform the metal using mechanical forces to achieve a specific shape and to improve certain properties. The forces required to deform the metal are very sensitive to the rate of load application and to temperature variations in hot working, but the basic strength of the metal is unchanged after deformation. On the other hand, the forces are relatively insensitive to the rate of load application and to temperature variations in cold working, but the basic strength of the steel is permanently changed after working. In addition to rolling, hot or cold working can take the forms of hammering, pressing, extrusion, piercing, upsetting, and drawing. In finish rolling, the number and type of stands depend on the shape being rolled and the relationship between percent reduction and rolling temperature per pass. Some of the finishing mills have facilities to coil the product, such as a strip mill or a wire mill. A plate, sheet, or a tube mill usually has facilities to clean the surface of superficial defects and scales by pickling and to apply corrosion-resistant coatings. Mills that roll concrete reinforcing bars also are capable of cold twisting the bar for strength. Ribs on the reinforcing bars are created by specially designed grooved rolls.

Direct rolling refers to finish rolling the continuously cast product with minimal or no reheating. The products are sent from the caster through a reheating furnace directly to finish rolling mills, such as a hot-strip mill, to conserve the heat of the as-cast product. Excellent surface quality is important because extensive conditioning of the material is not possible. Reheating for finish rolling is performed in either batch or continuous type of furnaces.

Continuous Hot-Strip Rolling

The term "strip mill" refers to a mill that continuously rolls sheet or strip. In a modern wide hot-strip mill, slabs are heated in two or more continuous reheating furnaces. A typical rolling mill train consists of a roughing scale breaker, followed by four four-high roughing stands, a finishing scale breaker, and six four-high finishing stands. In some recent installations, five roughing and seven finishing stands are used, in addition to the two scale breakers. Driven table rolls convey the material from the furnace to the mill and from stand to stand. As the steel proceeds from the mill, it is carried over a long table, called a runout table, where water is applied to the top and bottom surfaces of the strip by water sprays or laminar jets to reduce the strip temperature to a controlled value. Two or more coilers are located at the end of the runout table. Additional tables may be installed parallel to the central table with suitable mechanisms for moving material to them.

The hot-mill arrangement described previously employs continuous roughing and finishing trains and provides very high rolling capacity and rapid steel travel with little heat loss. However, it entails high installation costs and a fixed number of passes, with some loss of flexibility in making rapid changes in the mill setup when the size of the product to be rolled is changed. An alternative arrangement employs a reversing roughing mill and continuous finishing train; this arrangement has a lower installation cost and is flexible with regard to the number of passes available. If slabs are rolled directly from primary blooming operations and proceed for strip rolling using retained heat (direct rolling), slab reheating may be by-passed.

Quality aspects of finished strips include uniform reheating of slabs to produce a uniform scale jacket that can be dislodged readily during rolling. Insufficient soaking in reheating furnaces gives rise to scale which is difficult to remove. Other quality measures required to meet product standards are the consistency in surface, condition, gage, rolling width, finishing temperature, and cross-sectional contour. The water sprays play a vital roll in keeping the temperature at the desired value and in keeping the surfaces scalefree. It should be noted that metallurgical requirements dictate a definite finishing temperature. This temperature is affected by the holding time prior to coiling, the number of descaling sprays, the speed of the finishing train, and the method of drafting.

Coiling

Wide hot-rolled coils from a hot-strip mill can be used in the as-rolled condition, with or without pickling, shearing, and flattening, and are known as hot-rolled sheet. When used for cold reduction, coils are pickled and cold reduced by as much as 90%. Intermediate or post cold-work heat treatments may be done. The last hot-rolling operation at the last finishing stand should be conducted above the upper critical temperature. This practice allows the strip to pass through a phase transformation after all hot work is finished and produces a uniformly fine, equiaxed ferritic grain throughout all portions of the strip. For low-carbon steels, the finish rolling temperature is around 845 °C (1550 °F). If part of the hot rolling operation is carried out on steel below the critical temperature, the deformed ferrite grains usually recrystallize and form patches of abnormally coarse grains during the self anneal induced by coiling at the usual temperatures of 650 to 730 °C (1200 to 1345 °F). Such a structure is more likely to appear on the surface of the product, which is colder than the interior of the strip during rolling. Thus, very thin hot-rolled strips, finished far below the upper critical temperature with rolled ferrite, and coiled too cold to self anneal, may retain microstructural evidence of hot working. Such sheets or strips are not suitable for deep- or extra-deep drawing applications and may necessitate a subsequent normalizing treatment.

Steels in which the sum of the carbon plus manganese contents is below 0.10 wt% exhibit a hot-short temperature range between 900 and 1035 °C (1650 and 1900 °F). Normal hot rolling in this temperature range can produce deep cracks on the product edge. To remedy this situation, some mills complete the roughing operations above the hot-short range, to allow the steel to cool through the range by holding it on the conveyor table between the last roughing stand and the finishing train and to resume rolling by passing the product into the finishing train below the hot-short range. This practice does not allow finishing rolling above the upper critical temperature.

The runout table following the last rolling stand is long enough with sufficient cooling arrangement to lower the temperature by up to 350 °C (630 °F) below the finishing temperature before coiling. The cooling practice used at this stage largely determines the metallurgical properties of the final rolled product. These practices are referred to as the controlled rolling and accelerated cooling processes. A uniform microstructure with characteristic carbide morphology and ferrite grain size is established during this holding period before coiling. If the steel is coiled at around 730 °C (1345 °F), the self-annealing produces considerable and undesirable carbide agglomeration, a coarse ferrite grain, and a soft ductile sheet. Coiling around 650 °C (1200 °F) produces a fine, dispersed spheroidal carbide in a finer ferrite matrix, resulting in a harder steel with sufficient ductility. Because a coil has different cooling rates at the edge and center of the strip as well as the center and outer portions of the coil, uniformity in cooling is achieved by using forced cooling with fans or water sprays. Even coiling temperatures lower than 650 °C (1200 °F) can be used when martensitic or bainite microstructures are desired (see the sub-section "High-Strength Low-Alloy Steels").

Thermomechanical Processing

The improvements in steelmaking, ladle metallurgy/refining, and continuous casting practices have been matched with other advances in the science and technology of microstructural control in the final product. It is this ability to control microstructure during processing that has allowed significant and cost-effective improvements in the final properties of steel to be achieved. Central to the concept of controlled processing is thermomechanical processing.

It is now possible to produce as-rolled steels with final properties tailored to the requirements of the final application. The concept of tailored final properties is possible primarily through the ability of the steelmaker to control the final microstructure in a predictable manner. This control of the final microstructure is based on an understanding of the way that steels respond to hot processing and how that response can be altered through alloying (Ref 52).

It is well known that the control (that is, refinement) of final microstructure begins during solidification and proceeds during reheating, hot rolling, and final transformation. Because the final transformed microstructure reflects the microstructure and composition of the austenite prior to transformation, it is obvious that the refinement of this final austenite is critical to obtaining the optimal final microstructure and properties. One of the key processing elements used to obtain the proper austenite microstructure is known as thermomechanical processing. As discussed in the following paragraphs, the most common form of thermomechanical processing in use today is called controlled rolling. During controlled rolling, it is the as-rolled austenite microstructure that is being controlled.

Because the goal of thermomechanical processing is the refinement of the austenite grain structure, the control of recrystallization and/or grain coarsening during processing are among the metallurgical techniques available. The presence of minute quantities of elements such as niobium, titanium, and vanadium have been shown to be particularly useful during thermomechanical processing because of the change in the solubilities of their carbides/carbonitrides/nitrides in austenite as a function of temperature. These elements are known as microalloying elements because they are generally present at levels at or below 0.1 wt%. Hence, the use of these microalloying elements enables the goal of thermomechanical processing to be easily achieved because these elements permit forces retarding recrystallization and grain coarsening to be governed by controlled precipitation during processing. It is, therefore, normal to have microalloyed steel mentioned in discussions of thermomechanical processing. The role of finish reduction on the refinement of ferrite grain size and the resultant improvement in toughness of microalloyed steels is shown in Fig. 23.

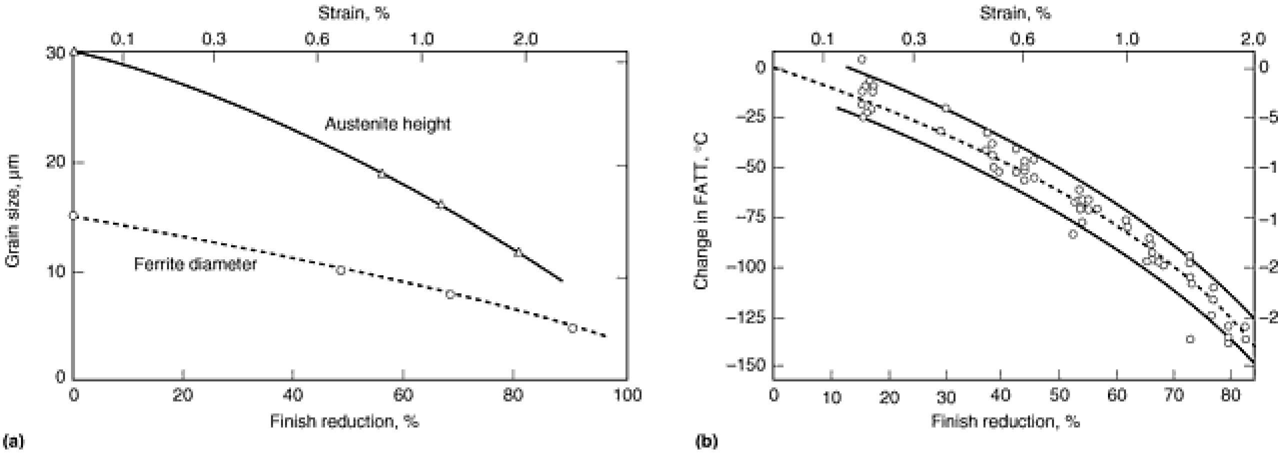

Fig. 23 Effect of percent finish reduction on the (a) austenite and ferrite grain size and (b) fracture toughness (fracture appearance transition temperature, or FATT) for a general class of microalloyed steels

Controlled Rolling. The hot-rolling process has gradually become a much more closely controlled operation, and controlled rolling is now being increasingly applied to microalloyed steels with compositions carefully chosen to provide optimal mechanical properties at room temperature. Controlled rolling is a procedure whereby the various stages of rolling are temperature controlled, with the amount of reduction in each pass predetermined and the finishing temperature precisely defined. This process is widely used to obtain reliable mechanical properties in steels for pipelines, bridges, offshore platforms, and many other engineering applications. The use of controlled rolling has resulted in improved combinations of strength and toughness and further reductions in the carbon content of microalloyed high-strength low-alloy (HSLA) steels. This reduction in carbon content improves not only toughness but also weldability.

As mentioned previously, the basic objective of controlled rolling is to refine and/or deform austenite grains during the rolling process so that fine ferrite grains are produced during cooling. Controlled rolling can be performed on carbon steels but is most beneficial in steels with vanadium and/or niobium additions. During hot rolling, the undissolved carbonitrides of vanadium and niobium pin austenite grain boundaries and thus retard austenite grain growth. In carbon steels, however, the temperatures involved in hot rolling lead to marked austenite grain growth, which basically limits any benefit of grain refinement by controlled rolling. Controlled rolling is performed on strip, plate, and bar mills but not on continuous hot strip mills. On a hot strip mill, the water cooling on the runout table ensures a fine grain size.

The three methods of controlled rolling are:

- Conventional controlled rolling
- Recrystallization controlled rolling
- Dynamic recrystallization controlled rolling

These three methods use different techniques for grain refinement, but they are all preceded by a roughing operation to refine grain size by repeated recrystallization. In the roughing stage, stable carbonitride precipitates are desirable because they pin the grain boundaries of the recrystallized austenite and thus prevent their growth. Niobium is more effective than vanadium in preventing austenite grain growth during rolling because niobium forms precipitates that are less soluble than vanadium carbide in austenite. Roughing can achieve austenite grain sizes on the order of 20 μm. The austenite grains are then either deformed or further refined by controlled rolling during finishing operations.

Conventional controlled rolling is based on the deformation, or flattening (pancaking), of austenite grains so that a large number of nucleation sites exist on the deformed austenite grain boundaries and on the deformation bands with the austenite grains. These nucleation sites allow the formation of very fine-grain ferrite during transformation cooling. This process requires a total reduction of up to 80% in a temperature range where the austenite deforms but does not recrystallize.

Niobium is the most effective alloying element for grain refinement by conventional controlled rolling. During the rolling reductions at temperatures below 1040 °C (1900 °F), the niobium in solution suppresses recrystallization by solute drag or by strain-induced Nb(C,N) precipitation on the deformed austenite and slip planes. The strain-induced precipitates are too large to affect precipitation strengthening but are beneficial for two reasons: They allow additional suppression of recrystallization by preventing migration of austenite grain subboundaries, and they provide a large number of nuclei in the deformed austenite for the formation of fine ferrite particles during cooling. The strain-induced precipitates in the austenite detract from the precipitation-hardening potential of the ferrite by removing the available niobium from austenite solid solution. Nevertheless, a useful measure of precipitation strengthening is possible in controlled-rolled niobium steels.

The controlled rolling of niobium steels can lead to ferrite grain sizes in the range of 5 to 10 μm (ASTM grain size numbers 10 to 12). Because the precipitation of Nb(C,N) in the austenite during hot rolling retards recrystallization and raises the temperature at which recrystallization of austenite ceases (the recrystallization stop temperature), a broader temperature range is possible for hot working the steel to produce highly deformed austenite. The optimal amount of niobium to suppress recrystallization between passes can be as little as 0.02%. Titanium, zirconium, and vanadium are not as effective as niobium in raising the recrystallization stop temperature. Titanium and zirconium nitride formed during solidification and upon cooling of the slab do not readily dissolve upon reheating to hot-rolling temperatures. Although these nitrides can prevent grain coarsening upon reheating, they are not effective in preventing recrystallization because insufficient titanium or zirconium remains in solution at the rolling temperature to precipitate on deformed austenite grain boundaries during hot rolling and thus suppress austenite recrystallization. Vanadium, on the other hand, is so soluble that precipitation does not readily occur in the austenite at normal hot-rolling temperatures. The concentrations of niobium, titanium, vanadium, carbon, and nitrogen; the degree of strain; the time between passes; the strain rate; and the temperature of deformation all influence recrystallization during hot working.

Recrystallization Controlled Rolling. Although conventional controlled rolling can lead to very fine ferrite grain sizes, the low finishing temperature (750 to 900 °C, or 1400 to 1650 °F) of this method leads to increased rolling loads for heavy plate and thick-walled seamless tube. For thicker sections, recrystallization controlled rolling is used to refine austenite grain size. This process can result in ferrite grain sizes on the order of 8 to 10 μm.

Recrystallization controlled rolling involves the recrystallization of austenite at successively lower temperatures below roughing temperatures, but still above 900 °C (1650 °F). Recrystallization should not be sluggish for this method to succeed, and thus vanadium can be beneficial because vanadium carbide is readily dissolved at rolling temperature and therefore unavailable for suppressing recrystallization. However, vanadium steels require stable carbonitrides, such as titanium nitride, to retard grain growth after recrystallization. Niobium steels, on the other hand, can undergo recrystallization controlled rolling at higher temperatures with Nb(C,N) precipitates eventually forming. This precipitation of Nb(C,N) will restrict austenite grain growth and may preclude the need for a titanium addition.

Dynamic recrystallization controlled rolling is used when there is insufficient time for recrystallization between rolling passes. This process initiates recrystallization during deformation and requires appreciable reductions (for example, 100%) to achieve an austenite grain size of 10 μm. With low-temperature finishing, dynamic recrystallization can result in ferrite grain as fine as 3 to 6 μm.

Accelerated Cooling. High-strength, control-rolled product can be obtained by low-temperature intercritical rolling combined with accelerated cooling through the transformation range. Faster cooling also retains solutes for subsequent precipitation strengthening of ferrite. If fine austenite is being transformed, fine polygonal ferrite pearlite or acicular ferrite-fine bainite with good strength and toughness can be obtained. Accelerated cooling must, therefore, be used in combination with controlled rolling, because coarse austenite can transform into upper bainite lowering the toughness considerably. Because accelerated cooling makes efficient use of both hardenability agents (such as molybdenum and boron) and microalloying additions, leaner and more economical steels with lower carbon equivalent can be used for higher strength, toughness, and weldability requirements.

The Stelmor process is another form of controlled accelerated cooling applied to wire and rod production in a continuous mill. In one form of Stelmor line applied to reinforcing bar production, the round product is passed through a water-spray box at very high speeds, causing the surface of the steel to quench and form martensite. However, as the wire is placed in the laying cone, the internal heat from the core of the product tempers the martensite producing a composite structure. The hard tempered surface provides strength and proper surface and scale characteristics while the core is tough with a predominantly ferrite-pearlite structure. Such a composite product is better suited as reinforcing bar without the need for cold twisting.

Pickling

The oxide scale on the surface of strip, sheet, plate, or semifinished products is not acceptable when the steel is to be further processed. If the steel is to be cold rolled or coated, as in galvanized, terne coated, or painted sheet and strip, removal of surface oxide is particularly important. In drawing operations, scale removal is essential to ensure a smooth finished surface and to protect the die from abrasive oxides. The surface scales are primarily iron oxides produced during hot rolling. The nature of the scale depends on the temperature and the gaseous environment. Common practices for the removal of scale include a physical method of shot blasting or a chemical method of pickling. Pickling involves chemical removal of oxides and scale from the surface by a water solution of inorganic acids, such as sulfuric or hydrochloric acid. Pickling equipment ranges from batch types to fully continuous picklers.

The chemical reaction of pickling acids with the metal produces a sulfate or chloride salt along with hydrogen gas. When scale reacts with the acids, water is produced instead of hydrogen. Nickel, chromium, and copper retard the dissolution of iron or the scale because the scales bearing these elements resist acid attack. Silicon and aluminum themselves form refractory oxides and lower the scale solubility rate. Iron is more readily attacked by the acids than the scale. Scales containing iron in higher oxidation states are more difficult to react. The rate of pickling is also dependent on the adherence of the scale. Solution temperature and concentration, ferrous sulfate concentration, agitation, time of immersion, and presence of inhibitors affect the rate of acid attack. Temperature has more pronounced effect than concentration. Typically, pickling baths are maintained at a temperature in the range of 65 to 80 °C (150 to 175 °F) and the rate is controlled by adjusting the concentration. Such a practice helps in saving fuel for heating and maintaining the inhibitor stability. Concentration of the pickling bath varies over a wide range depending on the amount of pickling required. Continuous baths are usually stronger and held at higher temperatures because pickling is required in a shorter time. Sulfuric acid baths range from 12 to 25% while hydrochloric acid baths range from 5 to 50% in acid concentration. Buildup of ferrous sulfate has a retarding effect on the pickling rate and a level of up to 25% is allowed to build. Much higher levels of ferrous chloride are allowed. Baths are usually worked until the free acid drops to 5%. Agitating either the workpiece or the liquid is a common practice that saves time, acid, and metal loss. Other bath additives include inhibitors, wetting agents, brightening agents, etc. Inhibitors lower the metal dissolution rate, enhance the attack on the scale and prevent foaming of the bath. Good inhibitors should be cheap and effective in smaller concentrations, while producing a stain-free clean metal surface. Wetting agents serve the purpose of lowering the surface tension between the bath and the steel surface. Brightening agents, as the name suggests, add to the brightness and smoothness of the surface.

Hydrochloric acid pickling provides a faster and cleaner pickling with less acid consumption and reduced quantities of waste pickle liquor. Because lower temperatures are used in hydrochloric acid pickling, steam consumption is ~40% lower. When compared to sulfuric acid pickling, hydrochloric acid pickling is 2.5 to 3.5 times faster at comparable temperatures and acid concentration. Hydrochloric acid is also more effective in removing embedded metal and scale particles. Typical acid consumption rates for sulfuric acid and hydrochloric acid vary between 15 to 22.5 kg and 5 to 7 kg per metric ton of steel, respectively. Hydrochloric acid baths provide greater versatility as scale breaking and temper rolling are usually not required for high-speed pickling, which is often a necessity in a sulfuric acid pickling line. Pickled surfaces are generally washed and dried before subsequent processing. Pickling prepares the surface for better bonding and adhesion in cases of galvanizing, coating, or a paint application (Ref 53).

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Specialized Processing Routes

Ultralow Plain Carbon Steels

The principal factors affecting the properties of the plain carbon steels are the carbon content and the microstructure. Manganese is a solid solution strengthener. The properties can be modified by the effects of residual elements other than carbon, manganese, silicon, phosphorus, and sulfur, which are usually picked up from the scrap, deoxidizers, and furnace refractories. In addition, gaseous hydrogen, nitrogen, and oxygen also affect steel properties, as has been mentioned earlier. Control of these extraneous agents is always critical during steelmaking. Steelmakers have adopted some very sophisticated processing techniques over the last two decades to achieve this end. Because carbon is the main element in plain carbon steels providing strength, carbon contents of less than 0.05% and manganese contents of the order of 0.20% are desired in steels intended for a high-level of cold formability. These steels are used for deep and extra-deep drawability and stretch formability applications, particularly in the automotive industry. The plastic strain ratio (*r*) and strain hardening exponent (*n*) are critical parameters along with high uniform elongation (Ref 54). Figure 24 shows the effect of carbon on some of the prominent mechanical properties reflecting high formability.

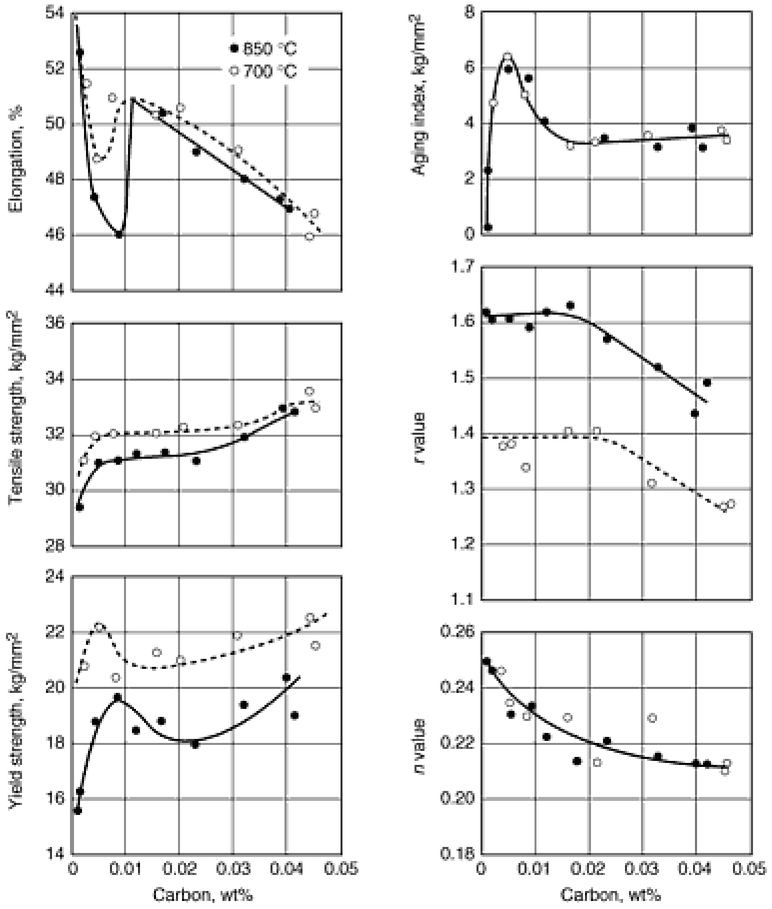

Fig. 24 Effect of carbon content on the mechanical properties of steels. Note: 1 kg/mm^2 = 9.806 MPa

Figure 25 shows a typical process route for ultralow carbon steels. The steel is fully killed with aluminum and the carbon and nitrogen levels are further lowered below 0.001% by niobium or titanium treatment during secondary steelmaking. The steel can then be cast into ingots or continuously cast. Soaking temperatures in excess of 1200 °C (2190 °F) to add aluminum nitride into solution and coiling below 560 °C (1040 °F) to suppress aluminum nitride precipitation are critical steps in processing. High-temperature coiling lowers the cooling rate in a tightly wound coil and causes nitride precipitation. Favorable texturing can be obtained by subsequent cold rolling and annealing of the hot-coiled material in thin gages. Aluminum nitride precipitates during annealing give rise to {111} texturing as well as ferrite grain growth. The highest strain ratios can be obtained by maintaining aluminum and nitrogen contents in the range of 0.025 to 0.04 % and 0.005 to 0.01%, respectively. High annealing temperatures (>730 °C, or 1350 °F) are avoided to prevent carbide coarsening and sticking of coil laps. Adjustment of cooling rate during annealing is practiced to retain some of the carbon in solid solution, which imparts strength to the sheets and strips of ultralow carbon steel. Continuous annealing of low-carbon materials can be adopted for lower carbon levels of less than 0.02%, whereas batch annealing can be used to process up to 0.05% carbon steels (Ref 55).

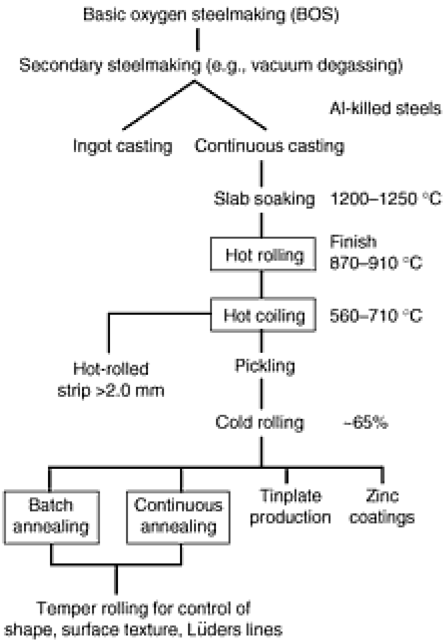
Basic oxygen steelmaking (BOS)
Secondary steelmaking (e.g., vacuum degassing)
Al-killed steels
Ingot casting
Continuous casting
Slab soaking
1200–1250 °C
Hot rolling
Finish 870–910 °C
Hot coiling
560–710 °C
Hot-rolled strip >2.0 mm
Pickling
Cold rolling
~65%
Batch annealing
Continuous annealing
Tinplate production
Zinc coatings
Temper rolling for control of shape, surface texture, Lüders lines

Fig. 25 Typical flow diagram for processing low-carbon strip steel

Interstitial-Free Steels

Flat-rolled steels with carbon less than 0.003% and manganese below 0.18%, with special emphasis on low nitrogen to prevent aging effects and low hydrogen to prevent flaking, are classified as interstitial-free steel. Lowering of carbon and nitrogen is achieved by niobium, titanium, and boron treatments during secondary steelmaking. A boron-to-nitrogen ratio of 0.8 to 1.0 is beneficial in these steels, because boron has a greater affinity for nitrogen than aluminum, allowing relatively higher coiling temperature. In such steels, titanium carbides raise the recrystallization temperature. Therefore, the steels are finish rolled above 950 °C (1740 °F). Interstitial-free steels are characterized by a high strain ratio of above 2.0, where excellent forming properties can be achieved by continuous annealing. Small additions of phosphorus (rephosphorized steel: up to 0.1% P), manganese, and silicon are sometimes used to impart some strength in interstitial-free steels and are known as interstital-free high-strength steels (IF-HSS). These steels maintain their formability without any impairment of weldability (Ref 56).

High-Strength Low-Alloy Steels

Both the interstitial-free steels and the ultralow plain carbon steels have low strength due to low carbon and manganese levels (tensile strength below ~300 MPa, or 40 ksi) and are not suitable for high-strength applications. These grades have been specifically designed for high formability. However, there is a strong interest in weldable, formable, high-strength flat products in both hot- and cold-rolled conditions. The need to use lighter gages for weight reduction while maintaining a high strength level (yield strengths ranging from 410 to 550 MPa, or 60 to 80 ksi, are common) and structural integrity, has led to the development of a microalloyed class of steel, known as high strength low alloy (HSLA) steels. A minimum tensile strength of 480 MPa (70 ksi) is achieved in some common grades of HSLA steels. Small additions of one or more of the alloying agents, such as vanadium, niobium, titanium, boron, zirconium, chromium, silicon, nitrogen, and/or copper are made to molten steel after ladle deoxidation or during secondary steelmaking to achieve one or more of the following objectives (Ref 57):

- Precipitation strengthening
- Solid-solution strengthening
- Ferrite grain-refinement
- Transformation strengthening

In addition, corrosion resistance, excellent weldability, and high room-temperature and low-temperature notch-toughness values are also desired in HSLA steels for specific applications. The specific role of each of these additions is discussed in

Ref 58. It should be emphasized that lowering the sulfur content in steels is desired for automotive grades, line pipe steels, and corrosion-resistant products (Ref 59). The influence of very small additions of microalloying elements on the properties of HSLA steels is clearly demonstrated in Fig. 26. A good deoxidation practice is essential for HSLA grades so that a high recovery of the alloying additions can be achieved. These steels are produced as flat-rolled sheet, strip, and plate materials as well as structural shapes, for example, line pipe tubulars, gas-container steels, reinforcing bars, cold-heading steel, etc.

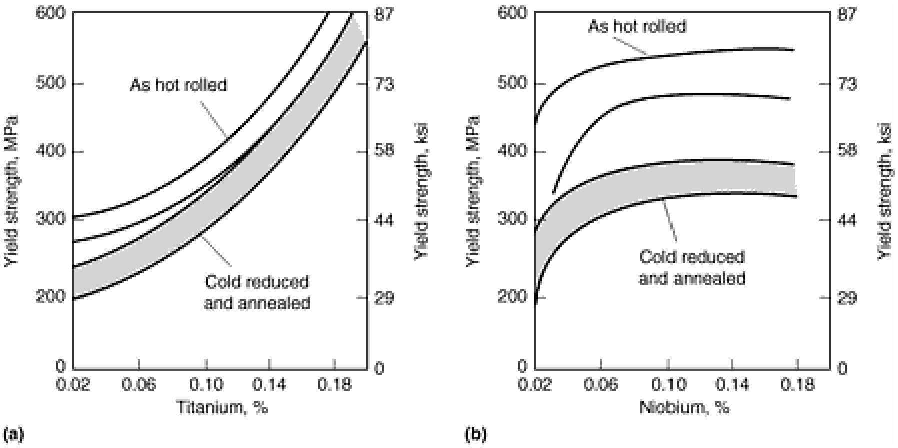

Fig. 26 Effect of microalloying on yield strength of hot- and cold-rolled steel strips

Ultrahigh Strength Steels

Several grades of engineering steels having ultrahigh strengths (over 1000 MPa, or 145 ksi, tensile strength) have been developed either through high-alloy additions of chomium, molybdenum, nickel, vanadium, and manganese in combination with low-carbon contents or through low-to-high alloy additions in combination with medium-to-high carbon levels (>0.40% C). The former type of high-alloy steels with low carbon are used for turbine blades, rings, bolts, and casings, whereas the latter medium-to-high, carbon-bearing steels are needed for high-strength rail steels, bearing steels, forging steels, tool steels, high-speed steels, and high-carbon wire rods. The important properties desired in these grades are high-room and elevated-temperature hardenability (through hardness or surface hardness) in combination with high toughness.

Quality of these ultrahigh strength steels has significantly improved with the introduction of vacuum degassing technology as well as inclusion shape control. Argon shrouding of the liquid stream during teeming and casting is practiced to prevent reoxidation and to reduce the non-metallic inclusion content while vacuum induction melting and vacuum arc remelting are common practices for producing exceptionally clean steels (Ref 60). Slag-free tapping, ladle stirring, and the use of high-alumina ladle refractories are some other integral aspects of clean steel production. Inclusion shape control is administered through lead, selenium, tellurium, calcium, bismuth, or rare-earths addition. Niobium, vanadium, or titanium are also added as microadditions for similar property enhancement similar to HSLA steels. Low-sulfur petroleum coke is usually the source for increasing carbon level. The recent commercialization of iron carbide can provide a better source for carburization of steel melts due to its low tramp element level and higher density than petroleum coke.

Cold-Rolled Products

Cold-rolled finished products include flat bars, cold-rolled strips and sheets, and black plate, which are made from plain carbon steels and alloyed steels, including stainless steels. Tempering, annealing, and edging are associated steps in cold rolling. The chosen processing scheme is dictated entirely by the application. Cold rolling implies passing unheated metal through rolls for thickness reduction, surface finish improvement, and controlled mechanical properties. The metal for cold rolling is generally produced in coiled form in a hot-strip mill. Prior to cold reduction, the hot-rolled coils are uncoiled, pickled, dried, oiled, and recoiled. The coils are reduced at very high speeds by looping the metal from one coil to the other. Heavy reductions of up to 90% may be taken in a single strand reversing mill or a tandem mill. The design of a cold-rolling process is based on the type of mill, power available, steel width, total reduction, steel hardness and tension, lubrication, and desired surface finish. On multiple-strand mills or a reversing mill, the last pass is primarily used for control of gage thickness, flatness, and surface finish and not for the purpose of reduction (Ref 61).

Cold-rolled material is sometimes used in the as-rolled condition to make use of its cold-worked high strength depending on the application. Generally, the metal requires heat treatment to control the mechanical properties. A surface cleaning step, either chemical, electrochemical, or mechanical, is taken before heat treatment. The low-carbon, deep-drawing type steels are usually annealed in a box furnace or a continuous furnace at a low temperature of ~675 °C (1250 °F) to encourage recovery and recrystallization while preventing any grain growth. Other types of heat treatments can be performed after cold reduction, for example, to solutionize chromium carbides in stainless steel strips or to form a passive oxide on transformer-grade, silicon-steel sheets.

Subsequent to heat treatment, a temper rolling may be necessary to achieve certain features in the product, such as suppression of yield-point elongation that causes Lüder lines (Ref 62), a bright surface finish, and surface flatness and shape improvements. Usually, the reduction achieved during temper rolling is restricted to below 2% to prevent a decrease in ductility. Shearing, side trimming, slitting, and leveling follow temper rolling of cold-rolled products.

Some prominent surface defects of cold-rolled products are seams and slivers that have their origin in the inclusions trapped during steel casting. When the steel gage is heavily reduced, nonmetallic inclusions appear on the surface and spall off. In addition, a critical aluminum to nickel balance is required in cold-rolled products for the development of favorable texturing. Thus, it can be readily seen that deoxidation, inclusion control, and nitrogen balance are key steelmaking factors in cold-rolled materials. Fully aluminum-killed steels, cast in wide-end-up molds after argon rinsing and under complete inert shrouding are known to possess enhanced mechanical and surface properties for cold-rolling application.

Stainless Steels

Iron-chromium steels, with possible additions of nickel and moybdenum, in combination with low carbon contents, are designated as "stainless steels" when a minimum of 12% Cr is present to provide a passive layer of chromium oxide on the surface. This passive layer is responsible for the high corrosion resistance realized in stainless steels. Stainless steel was traditionally made in small EAFs by melting steel scrap, nickel, and ferrochrome before the advent of oxygen refining. The modern practice of making stainless steel is based on a two-stage process. The first stage employs a conventional EAF for the rapid melting of scrap and ferroalloys but uses cheap high-carbon ferrochrome as the main source of chromium. Because stainless steel manufacturing involves more scrap melting and alloying and less refining, EAFs are preferred over the oxygen-based converter processes due to high external energy loads. The high-carbon melt prepared in an EAF is then refined in a second stage, using either AOD or by blowing with oxygen under VOD (see the section "Secondary Steelmaking"). The AOD process currently produces over 80% of the stainless steel tonnage worldwide. Special desulfurizing slags are used in AOD where intimate metal-slag mixing can be achieved using argon stirring. Oxygen is capable of decarburizing the melt to less than 0.01% C, and hydrogen levels are below 2 to 3 ppm. Sensitization in austenitic stainless steels leading to intergranular corrosion is markedly influenced by the presence of elongated particles or clusters of second phases, such as sulfides or other inclusions. The presence of nitrogen in some niobium-bearing stainless grades leads to carbonitride formation, which also deleteriously influences sensitizaton. Control of gaseous inclusions as well as sulfur are important in refining of stainless steels.

Stainless steels require expensive alloying additions of chromium, nickel, and molybdenum. Therefore, recovery of these elements needs special attention. Efficient slag reduction with stoichiometric amounts of silicon or aluminum permits overall recoveries of 97 to 100% for most metallic elements. Chromium recovery averages approximately 97.5%, and nickel and molybdenum recoveries are approximately 100%. Casting is usually done in a continuous caster for better productivity, although ingot casting and primary rolling is still more common for stainless steels than carbon steels. The cost of ferrochrome production affects stainless steel prices directly.

Commercial varieties of stainless steels are classified as austenitic (work hardenable), ferritic (work hardenable), austenitic-ferritic (duplex), or martensitic (hardenable by heat treatment). Although this classification is based on microstructure, it relates to two primary roles of alloy additions: (1) the balance between austenite formers (N, C, Ni, Co, Cu, and Mn) and ferrite formers (W, Si, Mo, Cr, V, and Al) controlling the high-temperature microstructure and (2) the overall alloy content, which controls the martensite transformation range, M_s-M_f, and the degree of martensite transformation at ambient temperature. Figure 27 (Ref 63) shows the effect of ferrite-forming (chromium equivalent) and austenite-forming (nickel equivalent) alloy additions on the type of stainless steel produced.

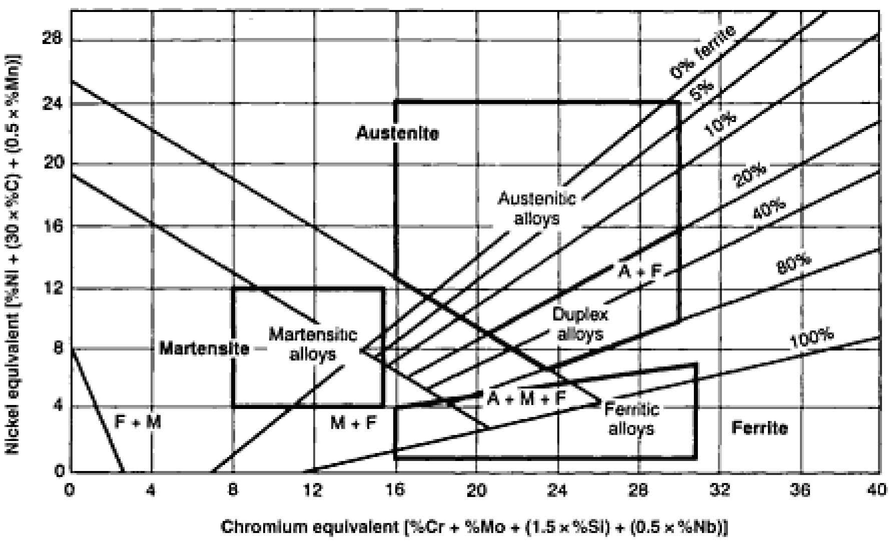

Fig. 27 Modified Schaeffler constitution diagram for stainless steels. The compositions of the ferritic, martensitic, austenitic, and duplex alloys are superimposed on this diagram.

Stainless steels have lower thermal conductivity than carbon or alloy steels below 815 °C (1500 °F) and, therefore, need special attention in heating below 815 °C (1500 °F) to avoid surface burning. In addition, hot-working temperature ranges for stainless steels are narrower than for carbon steels, requiring better temperature control during soaking and rolling. Martensitic grades are slow cooled or annealed after rolling because they are air hardening. Ferritic grades are finish rolled to lower temperatures to prevent grain growth that could lead to tearing and cracking. Austenitic grades require more rolling-mill power because they are stronger than ferritic grades and are also susceptible to grain growth. Sulfur control in reheating furnace atmospheres is important for austenitic grades due to the presence of nickel. Liquid nickel sulfide formation at the grain boundaries during rolling can lead to tears and cracks. Cold rolling of stainless steel has two primary objectives--reduction of hot-rolled gage and cold forming into components. Except the high-carbon grades, all stainless steels are amenable to cold working. Pickling is performed following hot rolling.

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Analytical Techniques for Liquid Steel

It cannot be overemphasized that properties of a steel are primarily determined by its chemical composition and that the steelmaker has no control of the composition once the metal is cast. The computerization of the primary and secondary steelmaking processes and the dramatic reduction in time required to make steel by modern methods has put tremendous pressure on the time available for liquid metal analysis. The chemist must return the chemical composition analysis of liquid steel rapidly so that corrective actions may be taken, if necessary. Unfortunately, the techniques available for rapid and accurate analysis are limited.

Chemical analysis is employed to determine whether or not material is within ordered chemical limits and sometimes to check the degree to which elements contained in the steel have segregated. Elemental analysis of carbon, silicon, sulfur, phosphorus, and manganese go hand in hand with oxygen and nitrogen gas measurements as well as the temperature monitoring. Usually, a pyrometer or an immersion thermocouple is employed to accurately measure the temperature. Consumable oxygen sensors are commonly used for on-line total oxygen analysis. However, the rapid determination of concentrations of alloying elements in steels is performed by the optical emission spectroscopy methods.

Optical emission spectroscopy can determine major as well as trace elemental constituents qualitatively and quantitatively. Free atoms emit light at a series of narrow wavelength intervals when placed in an energetic environment. These intervals, or emission lines, form a pattern, or the emission spectrum, which is characteristic of the atom producing it. The intensities of the lines are proportional to the number of atoms producing them. The presence of an element in a sample is indicated by the presence in light from the excitation source of one or more of its characteristic lines. The concentration of the element can be determined by measuring line intensities (Ref 64). The characteristic emission spectrum forms the basis for qualitative elemental analysis, whereas the measurement of intensities of the emission lines forms the basis for quantitative analysis.

The liquid sample is collected from the steelmaking furnace during the refining period or the ladle during secondary steelmaking and prior to casting. The sample is immediately cast into a form suitable for the spectroscope. Some surface grinding of the active surface may be done prior to analysis. An emission light source is used to decompose the sample into an atomic vapor and then excite the vapor with sufficient efficiency to produce a measurable emission signal. Four types of emission sources are available: arcs, high-voltage sparks, glow discharges, and flames. Each emission source has a set of physical characteristics with accompanying analytical capability and limitations.

Spark and glow-discharge emission sources are most common for rapid compositional analysis during steelmaking. Spark-source excitation is the most rapid method for analyzing an alloy sample. Analysis can be done in as little as thirty seconds and usually can be done within a couple of minutes. While flame sources are appropriate for analyzing trace levels of alkali metals down to a few ppm, glow-discharge source is more suited for carbon, phosphorus, and sulfur analysis. Detection limits are as low as 0.002% for sulfur and 0.014% for carbon.

Other analytical techniques suitable for chemical analysis of steels include atomic absorption spectroscopy, x-ray fluorescence, and inductively-coupled and direct-current plasma emission spectroscopies. Some of these techniques require the dissolution of samples in a solvent. Qualitative analysis of sulfur and phosphorus is also performed by sulfur and phosphorus prints, but these are not used for rapid analysis.

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Classifications and Designations of Carbon and Alloy Steels

Introduction

WROUGHT CARBON AND ALLOY STEELS with total alloying element contents that do not exceed 5% are considered in this article. Ferrous materials that are cast or made by powder metallurgy methods are not included, but are described elsewhere in this Handbook. The same is true for tool steels, more highly alloyed stainless steels, and steels used primarily for their magnetic or electrical properties (e.g., silicon steels).

Important Terms and Definitions

Classification is the systematic arrangement or division of steels into groups on the basis of some common characteristic. Steels can be classified on the basis of (1) composition, such as carbon or alloy steel; (2) manufacturing method, such as basic oxygen furnace steel or electric-arc furnace steel; (3) finishing method, such as hot-rolled or cold-rolled sheet; (4) microstructure, such as ferritic or martensitic; (5) the required strength level, as specified in ASTM standards; (6) heat treatment, such as annealed or quenched-and-tempered; (7) quality descriptors, such as forging quality or structural quality; or (8) product form, such as bar, plate, sheet, strip, tubing, or structural shape. Classification by product form is very common within the steel industry because by identifying the form of a product, the manufacturer can identify the mill equipment required for producing it and thereby schedule the use of these facilities.

Common usage has further subdivided these broad classifications. For example, carbon steels are often loosely and imprecisely classified according to carbon content as low-carbon (up to 0.30% C), medium-carbon (0.30 to 0.60% C), or high-carbon (0.60 to 1.00% C) steels. They may be classified as rimmed, capped, semikilled, or killed, depending on the deoxidation practice used in producing them. Alloy steels are often classified according to the principal alloying element (or elements) present. Thus, there are nickel steels, chromium steels, and chromium-vanadium steels, for example. Many other classification systems are in use, the names of which are usually self-explanatory.

Grade, type, and class are terms used to classify steel products. Within the steel industry, they have very specific uses: grade is used to denote chemical composition; type is used to indicate deoxidation practice; and class is used to describe some other attribute, such as strength level or surface smoothness.

In ASTM specifications, however, these terms are used somewhat interchangeably. In ASTM A 533, for example, type denotes chemical composition, while class indicates strength level. In ASTM A 515, grade identifies strength level; the maximum carbon content permitted by this specification depends on both plate thickness and strength level. In ASTM A 302, grade connotes requirements for both chemical composition and mechanical properties. ASTM A 514 and A 517 are specifications for high-strength plate for structural and pressure-vessel applications, respectively; each contains several compositions that can provide the required mechanical properties. A 514 type F has the identical composition limits as A 517 grade F.

Designation is the specific identification of each grade, type, or class of steel by a number, letter, symbol, name, or suitable combination thereof unique to a particular steel. Chemical composition is by far the most widely used basis for designation, followed by mechanical-property specifications. The most commonly used system of designation in the United States is that of SAE International (formerly the Society of Automotive Engineers) and the American Iron and Steel Institute (AISI). The Unified Numbering System (UNS) is also being used with increasing frequency. A description of each of these designation systems follows.

Quality. The steel industry uses the term "quality" in a product description to imply special characteristics that make the mill product particularly well suited to specific applications or subsequent fabrication operations. The term does not necessarily imply that the mill product is better material, is made from better raw materials, or is more carefully produced than other mill products.

A specification is a written statement of attributes that a steel must possess in order to be suitable for a particular application, as determined by processing and fabrication needs and engineering and service requirements. It generally includes a list of the acceptable values for various attributes that the steel must possess and, possibly, restrictions on other characteristics that might be detrimental to its intended use.

A standard specification is a published document that describes a product acceptable for a wide range of applications and that can be produced by many manufacturers of such items. Even if there is no standard specification that completely describes the attributes required for a steel product to be used in a particular application, it may be preferable to cite the most nearly applicable standard specification and those exceptions necessitated by the particular application. By doing so, the familiarity of both producer and user with the standard specification is retained, while an individualized product can be obtained.

A specification can be advantageously used in purchasing steel (or any other product) by incorporating it into the purchase agreement. The specification clearly states which attributes the product must possess. The use of a designation alone as the basis for purchase indicates that the buyer is specifying only those attributes described in the designation and permitting the supplier the latitude to produce the item according to his usual practice. The distinction between specifications and standard practices follows.

Quality Descriptors

The need for communication among producers and between producers and users has resulted in the development of a group of terms known as fundamental quality descriptors. These are names applied to various steel products to imply that the particular products possess certain characteristics that make them especially well suited for specific applications or fabrication processes. The fundamental quality descriptors in common use are listed in Table 1.

Table 1 Quality descriptions of carbon and alloy steels

Carbon steels
Semifinished for forging **Forging quality** Special hardenability Special internal soundness Nonmetallic inclusion requirement Special surface
Carbon steel structural sections **Structural quality**
Carbon steel plates **Regular quality** **Structural quality** **Cold-drawing quality** **Cold-pressing quality** **Cold-flanging quality** **Forging quality** **Pressure vessel quality**
Hot-rolled carbon steel bars **Merchant quality** **Special quality** Special hardenability Special internal soundness Nonmetallic inclusion requirement

Special surface **Scrapless nut quality** **Axle shaft quality** **Cold extrusion quality** **Cold-heading and cold-forging quality**
Cold-finished carbon steel bars **Standard quality** Special hardenability Special internal soundness Nonmetallic inclusion requirement Special surface **Cold-heading and cold-forging quality** **Cold extrusion quality**
Hot-rolled sheets **Commercial quality** **Drawing quality** **Drawing quality special killed** **Structural quality**
Cold-rolled sheets **Commercial quality** **Drawing quality** **Drawing quality special killed** **Structural quality**
Porcelain enameling sheets **Commercial quality** **Drawing quality** **Drawing quality special killed**
Long terne sheets **Commercial quality** **Drawing quality** **Drawing quality special killed** **Structural quality**
Galvanized sheets **Commercial quality** **Drawing quality** **Drawing quality special killed** **Lock-forming quality**
Electrolytic zinc coated sheets **Commercial quality** **Drawing quality** **Drawing quality special killed**

Structural quality
Hot-rolled strip **Commercial quality** **Drawing quality** **Drawing quality special killed** **Structural quality**
Cold-rolled strip **Specific quality descriptions are not provided in cold-rolled strip because this product is largely produced for specific end use**
Tin mill products **Specific quality descriptions are not applicable to tin mill products**
Carbon steel wire **Industrial quality wire** **Cold extrusion wires** **Heading, forging, and roll-threading wires** **Mechanical spring wires** **Upholstery spring construction wires** **Welding wire**
Carbon steel flat wire **Stitching wire** **Stapling wire**
Carbon steel pipe
Structural tubing
Line pipe
Oil country tubular goods
Steel specialty tubular products **Pressure tubing** **Mechanical tubing** **Aircraft tubing**
Hot-rolled carbon steel wire rods **Industrial quality** **Rods for manufacture of wire intended for electrical welded chain** **Rods for heading, forging, and roll-threading wire** **Rods for lock washer wire** **Rods for scrapless nut wire**

Rods for upholstery spring wire
Rods for welding wire

Alloy steels

Alloy steel plates

- Drawing quality
- Pressure vessel quality
- Structural quality
- Aircraft physical quality

Hot-rolled alloy steel bars

- Regular quality
- Aircraft quality or steel subject to magnetic particle inspection
- Axle shaft quality
- Bearing quality
- Cold-heading quality
- Special cold-heading quality
- Rifle barrel quality, gun quality, shell or armor-piercing shot quality

Alloy steel wire

- Aircraft quality
- Bearing quality
- Special surface quality

Cold-finished alloy steel bars

- Regular quality
- Aircraft quality or steel subject to magnetic particle inspection
- Axle shaft quality
- Bearing shaft quality
- Cold-heading quality
- Special cold-heading quality
- Rifle barrel quality, gun quality, shell or armor-piercing shot quality

Line pipe

Oil country tubular goods

Steel specialty tubular goods

- Pressure tubing
- Mechanical tubing
- Stainless and head-resisting pipe, pressure tubing, and mechanical tubing
- Aircraft tubing
- Pipe

Some of the quality descriptors listed in Table 1, such as forging quality or cold extrusion quality, are self-explanatory. The meaning of others is less obvious: for example, merchant quality hot-rolled carbon steel bars are made for noncritical applications requiring modest strength and mild bending or forming, but not requiring forging or heat treating. The descriptor for one particular steel commodity is not necessarily carried over to subsequent products made from that commodity, for example, standard quality cold-finished bars are made from special quality hot-rolled bars.

The various mechanical and physical attributes implied by a quality descriptor arise from the combined effects of several factors, including: (1) the degree of internal soundness; (2) the relative uniformity of chemical composition; (3) the relative freedom from surface imperfections; (4) the size of the discard cropped from the ingot; (5) extensive testing during manufacture; (6) the number, size, and distribution of nonmetallic inclusions; and (7) hardenability requirements. Control of these factors during manufacture is necessary to achieve mill products having the desired characteristics. The extent of the control over these and other related factors is also conveyed by the quality descriptor.

Some, but not all, of the fundamental descriptors can be modified by one or more additional requirements as appropriate: special discard, macroetch test, restricted chemical composition, maximum incidental (residual) alloy, special hardenability, or austenitic grain size. These restrictions could be applied to forging quality alloy steel bars, but not to merchant quality bars.

Understanding the various quality descriptors is complicated by the fact that most of the requirements that qualify a steel for a particular descriptor are subjective. Only nonmetallic inclusion count, restrictions on chemical composition ranges and incidental alloying elements, austenitic grain size, and special hardenability are quantified. The subjective evaluation of the other characteristics depends on the skill and experience of those who make the evaluation. Although these subjective quality descriptors might seem imprecise and unworkable, steel products made to meet the requirements of a particular quality descriptor have those characteristics necessary for use in the indicated application or fabrication operation.

Specifications

A specification is a written statement of the requirements, both technical and commercial, that a product must meet; it is a document that controls procurement. There are nearly as many formats for specifications as there are groups writing them, but any reasonably adequate specification will provide information about:

- *Scope,* which can cover product classification (including size range when necessary), condition, and any comments on product processing deemed helpful to either the supplier or user. An informative title plus a statement of the required form can be used instead of a scope clause.
- *Chemical composition,* which can be detailed or indicated by a well-recognized designation based on chemical composition. The SAE-AISI designations are frequently used.
- *The quality statement,* which includes any appropriate quality descriptor and whichever additional requirements are necessary. It can also include the type of steel and the steelmaking processes permitted.
- *Quantitative requirements,* which identify allowable ranges of the composition and all physical and mechanical properties necessary to characterize the material. Test methods used to determine these properties should also be included, at least by reference to standard test methods. For reasons of economy, this section should be limited to properties that are germane to the intended application.
- *Additional requirements,* which can include special tolerances, surface preparation, and edge finish on flat-rolled products, as well as special identification, packaging, and loading instructions.

Engineering societies, associations, and institutes whose members make, specify, or purchase steel products publish standard specifications, many of which have become well known and highly respected. Some of the important specification-writing groups are listed below. It is obvious from the names of some of these that the specifications prepared by a particular group may be limited to its own specialized field:

Organization	**Acronym**
Association of American Railroads	AAR

American Bureau of Shipbuilding	ABS
American Petroleum Institute	API
American Railway Engineering Association	AREA
American Society of Mechanical Engineers	ASME
American Society for Testing and Materials	ASTM
Society of Automotive Engineers	SAE
Aerospace Material Specification (of SAE)	AMS

The most comprehensive and widely used specifications are those published by ASTM. ASTM specifications pertaining to steel products exist at three distinct levels. ASTM A 6 contains the general requirements for most carbon steel structural products. ASTM A 588, for example, incorporates the general requirements of A 6 and describes the more specific requirements of a family of high-strength low-alloy (HSLA) steels. Other specifications, such as A 231 for alloy steel spring wire, refer to a particular product intended for a specific application.

Other specifications for steel products have been prepared by various corporations and United States government agencies to serve their own special needs. They are used primarily for procurement by that corporation or agency, and they receive only limited distribution or use beyond these channels.

There is an important difference between specifications and standard practices. As indicated above, a specification is a statement of the requirements that a product must meet. When it is cited by a purchaser and accepted by a supplier, it becomes part of the purchase agreement. Many manufacturers of steel mill products publish compilations of their standard manufacturing practices. These data represent the dimensions, tolerances, and properties that might be expected in the absence of specific requirements that indicate otherwise. The AISI *Steel Products Manuals* are compilations of the AISI designations for carbon and alloy steels, the standard practices of many steelmakers, and related scientific and technical information that has been reported to the institute. AISI states that the *Steel Products Manuals* are not specifications; however, they are a good indication of what restrictions and tolerances many producers of steel mill products will accept. Commercial tolerances and practices described in these manuals should, whenever possible, be incorporated into a proprietary specification in order to minimize the additional cost incurred by ordering "nonstandard" steel products.

Chemical Analysis

Chemical composition is often used as the basis for classifying steels or assigning standard designations to steels. Such designations are often incorporated into specifications for steel products. Users and specifiers of steel products should be familiar with methods of sampling and analysis.

Chemical analyses of steels are usually performed by wet chemical analysis methods or spectrochemical methods. Wet analysis is most often used to determine the composition of small numbers of specimens or of specimens composed of machine tool chips. Spectrochemical analysis is well-suited to the routine determination of the chemical composition of a large number of specimens, as may be necessary in a steel mill environment. Both classical wet chemical and spectrochemical methods for analyzing steel samples are described in detail in *Materials Characterization,* Volume 10, *ASM Handbook.*

Heat and Product Analysis. During the steelmaking process, a small sample of molten metal is removed from the ladle or steelmaking furnace, allowed to solidify, and then analyzed for alloy content. In most steel mills, these heat analyses are performed using spectrochemical methods; as many as 14 different elements can be determined simultaneously. The heat analysis furnished to the customer, however, may include only those elements for which a range or a maximum or minimum limit exists in the appropriate designation or specification.

A heat analysis is generally considered to be an accurate representation of the composition of the entire heat of metal. Producers of steel have found that heat analyses for carbon and alloy steels can be consistently held within ranges that depend on the amount of the particular alloying element desired for the steel, the product form, and the method of making the steel. These ranges have been published as commercial practice, then incorporated into standard specifications. Standard ranges and limits of heat analyses of carbon and alloy steels are given in Tables 2, 3, 4, and 5.

Table 2 Carbon steel cast or heat chemical limits and ranges

Applicable only to semifinished products for forging, hot-rolled and cold-finished bars, wire rods, and seamless tubing

Element	**Maximum of specified element, %**	**Range, %**
Carbon[a]	$\leq$0.12	. . .
	>0.12-0.25 incl	0.05
	>0.25-0.40 incl	0.06
	>0.40-0.55 incl	0.07
	>0.55-0.80 incl	0.10
	>0.80	0.13
Manganese	$\leq$0.40	0.15
	>0.40-0.50 incl	0.20
	>0.50-1.65 incl	0.30
Phosphorus	>0.40-0.08 incl	0.03
	>0.08-0.13 incl	0.05
Sulfur	>0.050-0.09 incl	0.03
	>0.09-0.15 incl	0.05
	>0.15-0.23 incl	0.07
	>0.23-0.35 incl	0.09

Silicon (for bars)[(b)(c)]	$\leq$0.15	0.08
	>0.15-0.20 incl	0.10
	>0.20-0.30 incl	0.15
	>0.30-0.60 incl	0.20
Copper	When copper is required, 0.20 minimum is commonly used	
Lead[(d)]	When lead is required, a range of 0.15-0.35 is generally used	

Incl, inclusive. Boron-treated fine-grain steels are produced to a range of 0.0005-0.003% B.

(a) The carbon ranges shown customarily apply when the specified maximum limit for manganese does not exceed 1.10%. When the maximum manganese limit exceeds 1.10%, it is customary to add 0.01 to the carbon range shown.

(b) It is not common practice to produce a rephosphorized and resulfurized carbon steel to specified limits for silicon because of its adverse effect on machinability.

(c) When silicon is required for rods the following ranges and limits are commonly used: 0.10 max; 0.07-0.15, 0.10-0.20, 0.15-0.35, 0.20-0.40, or 0.30-0.60.

(d) Lead is reported only as a range of 0.15-0.35% because it is usually added to the mold or ladle stream as the steel is poured

Table 3 Carbon steel cast or heat chemical limits and ranges

Applicable only to structural shapes, plates, strip, sheets, and welding tubing

Element	**Maximum of specified element, %**	**Range, %**
Carbon[(a)(b)]	$\leq$0.15	0.05
	>0.15-0.30 incl	0.06
	>0.30-0.40 incl	0.07
	>0.40-0.60 incl	0.08
	>0.60-0.80 incl	0.11
	>0.80-1.35 incl	0.14

Manganese	$\leq$0.50	0.20
	>0.050-1.15 incl	0.30
	>1.15-1.65 incl	0.35
Phosphorus	$\leq$0.08	0.03
	>0.08-0.15 incl	0.05
Sulfur	$\leq$0.08	0.03
	>0.08-0.15 incl	0.05
	>0.15-0.23 incl	0.07
	>0.23-0.33 incl	0.10
Silicon	$\leq$0.15	0.08
	>0.15-0.30 incl	0.15
	>0.30-0.60 incl	0.30
Copper	When copper is required, 0.20% minimum is commonly specified	

Incl, inclusive.

(a) The carbon ranges shown in the range column apply when the specified maximum limit for manganese does not exceed 1.00%. When the maximum manganese limit exceeds 1.00%, add 0.01 to the carbon ranges shown in the table.

(b) Maximum of 0.12% C for structural shapes and plates

Table 4 Alloy steel heat composition ranges and limits for bars, blooms, billets, and slabs

Element	**Maximum of specified element, %**	**Range, %**	
		Open hearth or basic oxygen steels	**Electric furnace steels**
Carbon	$\leq$0.55	0.05	0.05

	>0.55-0.70 incl	0.08	0.07
	>0.70-0.80 incl	0.10	0.09
	>0.80-0.95 incl	0.12	0.11
	>0.95-1.35 incl	0.13	0.12
Manganese	≤0.60	0.20	0.15
	>0.60-0.90 incl	0.20	0.20
	>0.90-1.05 incl	0.25	0.25
	>1.05-1.90 incl	0.30	0.30
	>1.90-2.10 incl	0.40	0.35
Sulfur(a)	≤0.050	0.015	0.015
	>0.050-0.07 incl	0.02	0.02
	>0.07-0.10 incl	0.04	0.04
	>0.10-0.14 incl	0.05	0.05
Silicon	≤0.15	0.08	0.08
	>0.15-0.20 incl	0.10	0.10
	>0.20-0.40 incl	0.15	0.15
	>0.40-0.60 incl	0.20	0.20
	>0.60-1.00 incl	0.30	0.30
	>1.00-2.20 incl	0.40	0.35
Chromium	≤0.40	0.15	0.15

	>0.40-0.90 incl	0.20	0.20
	>0.90-1.05 incl	0.25	0.25
	>1.05-1.60 incl	0.30	0.30
	>1.60-1.75 incl	(b)	0.35
	>1.75-2.10 incl	(b)	0.40
	>2.10-3.99 incl	(b)	0.50
Nickel	≤0.50	0.20	0.20
	>0.50-1.50 incl	0.30	0.30
	>1.50-2.00 incl	0.35	0.35
	>2.00-3.00 incl	0.40	0.40
	>3.00-5.30 incl	0.50	0.50
	>5.30-10.00 incl	1.00	1.00
Molybdenum	≤0.10	0.05	0.05
	>0.10-0.20 incl	0.07	0.07
	>0.20-0.50 incl	0.10	0.10
	>0.50-0.80 incl	0.15	0.15
	>0.80-1.15 incl	0.20	0.20
Tungsten	≤0.50	0.20	0.20
	>0.50-1.00 incl	0.30	0.30
	>1.00-2.00 incl	0.50	0.50

	>2.00-4.00 incl	0.60	0.60
Copper	≤0.60	0.20	0.20
	>0.60-1.50 incl	0.30	0.30
	>1.50-2.00 incl	0.35	0.35
Vanadium	≤0.25	0.05	0.05
	>0.25-0.50 incl	0.10	0.10
Aluminum	≤0.10	0.05	0.05
	>0.10-0.20 incl	0.10	0.10
	>0.20-0.30 incl	0.15	0.15
	>0.30-0.80 incl	0.25	0.25
	>0.80-1.30 incl	0.35	0.35
	>1.30-1.80 incl	0.45	0.45

Element	**Steelmaking process**	**Lowest maximum[(c)], %**
Phosphorus	Basic open hearth, basic oxygen, or basic electric furnace steels	0.035[(d)]
	Basic electric furnace E steels	0.025
	Acid open hearth or electric furnace steel	0.050
Sulfur	Basic open hearth, basic oxygen, or basic electric furnace steels	0.040[(d)]
	Basic electric furnace E steels	0.025
	Acid open hearth or electric furnace steel	0.050

Incl, inclusive.

(a) A range of sulfur content normally indicates a resulfurized steel.

(b) Not normally produced by open hearth process.

(c) Not applicable to rephosphorized or resulfurized steels.

(d) Lower maximum limits on phosphorus and sulfur are required by certain quality descriptors.

Table 5 Alloy steel heat composition ranges and limits for plates

Element	**Maximum of specified element, %**	**Range, %**	
		Open hearth or basic oxygen steels	**Electric furnace steels**
Carbon	$\leq$0.25	0.06	0.05
	>0.25-0.40 incl	0.07	0.06
	>0.40-0.55 incl	0.08	0.07
	>0.55-0.70 incl	0.11	0.10
	>0.70	0.14	0.13
Manganese	$\leq$0.45	0.20	0.15
	>0.45-0.80 incl	0.25	0.20
	>0.80-1.15 incl	0.30	0.25
	>1.15-1.70 incl	0.35	0.30
	>1.70-2.10 incl	0.40	0.35
Sulfur	$\leq$0.060	0.02	0.02
	>0.060-0.100 incl	0.04	0.04
	>0.100-0.140 incl	0.05	0.05

Silicon	≤0.15	0.08	0.08
	>0.15-0.20 incl	0.10	0.10
	>0.20-0.40 incl	0.15	0.15
	>0.40-0.60 incl	0.20	0.20
	>0.60-1.00 incl	0.30	0.30
	>1.00-2.20 incl	0.40	0.35
Copper	≤0.60	0.20	0.20
	>0.60-1.50 incl	0.30	0.30
	>1.50-2.00 incl	0.35	0.35
Nickel	≤0.50	0.20	0.20
	>0.50-1.50 incl	0.30	0.30
	>1.50-2.00 incl	0.35	0.35
	>2.00-3.00 incl	0.40	0.40
	>3.00-5.30 incl	0.50	0.50
	>5.30-10.00 incl	1.00	1.00
Chromium	≤0.40	0.20	0.15
	>0.40-0.80 incl	0.25	0.20
	>0.80-1.05 incl	0.30	0.25
	>1.05-1.25 incl	0.35	0.30
	>1.25-1.75 incl	0.50	0.40

	>1.75-3.99 incl	0.60	0.50
Molybdenum	≤0.10	0.05	0.05
	>0.10-0.20 incl	0.07	0.07
	>0.20-0.50 incl	0.10	0.10
	>0.50-0.80 incl	0.15	0.15
	>0.80-1.15 incl	0.20	0.20
Vanadium	≤0.25	0.05	0.05
	>0.25-0.50 incl	0.10	0.10

Incl, inclusive. Boron steels can be expected to contain a minimum of 0.0005% B. Alloy steels can be produced with a lead range of 0.15-0.35%. A heat analysis for lead is not determinable because lead is added to the ladle stream while each ingot is poured.

Because segregation of some alloying elements is inherent in the solidification of an ingot, different portions will have local chemical compositions that differ slightly from the average composition. Many lengths of bar stock can be made from a single ingot; therefore, some variation in composition between individual bars must be expected. The compositions of individual bars might not conform to the applicable specification, even though the heat analysis does. The chemical composition of an individual bar (or other product) taken from a large heat of steel is called the product analysis or check analysis. Ranges and limits for product analyses are generally broader and less restrictive than the corresponding ranges and limits for heat analyses. Such limits used in standard commercial practice are given in Tables 6, 7, and 8.

Table 6 Product analysis tolerances for carbon and alloy steel plates, sheet, piling, and bars for structural applications

Element	**Upper limit or maximum specified values, %**	**Tolerance, %**	
		Under minimum limit	**Over maximum limit**
Carbon	≤0.15	0.02	0.03
	>0.15-0.40 incl	0.03	0.04
Manganese(a)	≤0.60	0.05	0.06
	>0.60-0.90 incl	0.06	0.08

	>0.90-1.20 incl	0.08	0.10
	>1.20-1.35 incl	0.09	0.11
	>1.35-1.65 incl	0.09	0.12
	>1.65-1.95 incl	0.11	0.14
	>1.95	0.12	0.16
Phosphorus	≤0.04	. . .	0.010
	>0.04-0.15 incl	. . .	(b)
Sulfur	≤0.05	. . .	0.010
Silicon	≤0.30	0.02	0.03
	>0.30-0.40 incl	0.05	0.05
	>0.40-2.20 incl	0.06	0.06
Nickel	≤1.00	0.03	0.03
	>1.00-2.00 incl	0.05	0.05
Chromium	≤0.90	0.04	0.04
	>0.90-2.10 incl	0.06	0.06
Molybdenum	≤0.20	0.01	0.01
	>0.20-0.40 incl	0.03	0.03
	>0.40-1.15 incl	0.04	0.04
Copper	0.20 minimum only	0.02	. . .
	≤1.00	0.03	0.03

	>1.00-2.00 incl	0.05	0.05
Titanium	≤0.10	0.01(c)	0.01(c)
Vanadium	≤0.10	0.01(c)	0.01(c)
	>0.10-0.25 incl	0.02	0.02
	Minimum only specified	0.01	. . .
Boron	Any	(b)	(b)
Niobium	≤0.10	0.01(c)	0.01(c)
Zirconium	≤0.15	0.03	0.03
Nitrogen	≤0.030	0.005	0.005

Incl, inclusive.

(a) Manganese product analyses tolerances for bars and bar size shapes: ≤0.90, ±0.03; >0.90-2.20 incl, ±0.06.

(b) Product analysis not applicable.

(c) If the minimum of the range is 0.01%, the under tolerance is 0.005%.

Table 7 Product analysis tolerances for carbon and alloy steel bars, blooms, billets, and slabs

Element	**Limit or maximum of specified range, %**	**Tolerance over the maximum limit or under the minimum limit, %**			
		≤0.065 m^2 (100 $in.^2$)	**>0.065-0.129 m^2 (100-200 $in.^2$) incl**	**>0.129-0.258 m^2 (200-400 $in.^2$) incl**	**>0.258-0.516 m^2 (400-800 $in.^2$) incl**
Carbon	≤0.25	0.02	0.03	0.04	0.05
	>0.25-0.55 incl	0.03	0.04	0.05	0.06
	>0.55	0.04	0.05	0.06	0.07
Manganese	≤0.90	0.03	0.04	0.06	0.07

	>0.90-1.65 incl	0.06	0.06	0.07	0.08
Phosphorus[a]	Over maximum only, ≤0.40	0.008	0.008	0.010	0.015
Sulfur[a]	Over maximum only, ≤0.050	0.008	0.010	0.010	0.015
Silicon	≤0.35	0.02	0.02	0.03	0.04
	>0.35-0.60 incl	0.05	. . .	. . .	. . .
Copper	Under minimum only	0.02	0.03	. . .	. . .
Lead[b]	0.15-0.35 incl	0.03	0.03	. . .	. . .

Incl, inclusive. Rimmed or capped steels and boron are not subject to product analysis tolerances. Product analysis tolerances for alloy elements in high-strength low-alloy steels are given in Table 8.

(a) Because of the degree to which phosphorus and sulfur segregate, product analysis tolerances for those elements are not applicable for rephosphorized and resulfurized steels.

(b) Product analysis for lead applies, both over and under the specified range.

Table 8 Product analysis tolerances for alloy steel bars, blooms, billets, and slabs

Element	**Limit or maximum of specified range, %**	**Tolerance over the maximum limit or under the minimum limit for size ranges shown, %**			
		≤0.065 m^2 (100 $in.^2$)	**>0.065-0.129 m^2 (100-200 $in.^2$) incl**	**>0.129-0.258 m^2 (200-400 $in.^2$) incl**	**>0.258-0.516 m^2 (400-800 $in.^2$) incl**
Carbon	≤0.30	0.01	0.02	0.03	0.04
	>0.30-0.75	0.02	0.03	0.04	0.05
	>0.75	0.03	0.04	0.05	0.06
Manganese	≤0.90	0.03	0.04	0.05	0.06
	>0.90-2.10 incl	0.04	0.05	0.06	0.07
Phosphorus	Over max only	0.005	0.010	0.010	0.010

Sulfur	Over max only(a)	0.005	0.010	0.010	0.010
Silicon	≤0.40	0.02	0.02	0.03	0.04
	>0.40-2.20 incl	0.05	0.06	0.06	0.07
Nickel	≤1.00	0.03	0.03	0.03	0.03
	>1.00-2.00 incl	0.05	0.05	0.05	0.05
	>2.00-5.30 incl	0.07	0.07	0.07	0.07
	>5.30-10.00 incl	0.10	0.10	0.01	0.10
Chromium	≤0.90	0.03	0.04	0.04	0.05
	>0.90-2.10 incl	0.05	0.06	0.06	0.07
	>2.10-3.99 incl	0.10	0.10	0.12	0.14
Molybdenum	≤0.20	0.01	0.01	0.02	0.03
	>0.20-0.40 incl	0.02	0.03	0.03	0.04
	>0.40-1.15 incl	0.03	0.04	0.05	0.06
Vanadium	≤0.10	0.01	0.01	0.01	0.01
	>0.10-0.25 incl	0.02	0.02	0.02	0.02
	>0.25-0.50 incl	0.03	0.03	0.03	0.03
	Min value specified, check under min limit(b)	0.01	0.01	0.01	0.01
Tungsten	≤1.00	0.04	0.05	0.05	0.06
	>1.00-4.00 incl	0.08	0.09	0.10	0.12
Aluminum(c)	≤0.10	0.03	. . .	. . .	. . .

	>0.10-0.20 incl	0.04	. . .	. . .	. . .
	>0.20-0.30 incl	0.05	. . .	. . .	. . .
	>0.30-0.80 incl	0.07	. . .	. . .	. . .
	>0.80-1.80 incl	0.10	. . .	. . .	. . .
Lead(c)	0.15-0.35 incl	0.03(d)	. . .	. . .	. . .
Copper(c)	≤1.00	0.03	. . .	. . .	. . .
	>1.00-2.00 incl	0.05	. . .	. . .	. . .
Titanium(c)	≤0.10	0.01(b)	. . .	. . .	. . .
Niobium(c)	≤0.10	0.01(b)	. . .	. . .	. . .
Zirconium(c)	≤0.15	0.03	. . .	. . .	. . .
Nitrogen(c)	≤0.030	0.005	. . .	. . .	. . .

Incl, inclusive. Boron is not subject to product analysis tolerances.

(a) Resulfurized steels are not subject to product analysis limits for sulfur.

(b) If the minimum range is 0.01%, the under tolerance is 0.005%.

(c) Tolerances shown apply only to 0.065 m^2 (100 in.^{2}) or less.

(d) Tolerance is over and under.

Residual elements usually enter steel products from raw materials used to produce pig iron or from scrap steel used in steelmaking. Through careful steelmaking practices, the amounts of these residual elements are generally held to acceptable levels. Sulfur and phosphorus are usually considered deleterious to the mechanical properties of steels; therefore, restrictions are placed on the allowable amounts of these elements for most grades. The amounts of sulfur and phosphorus are invariably reported in the analyses of both carbon and alloy steels. Other residual alloying elements generally exert a lesser influence than sulfur and phosphorus on the properties of steel. For many grades of steel, limitations on the amounts of these residual elements are either optional or omitted entirely. Amounts of residual alloying elements are generally not reported in either heat or product analyses, except for special reasons.

Silicon Content of Steels. The composition requirements for many steels, particularly plain carbon steels, contain no specific restriction on silicon content. The lack of a silicon requirement is not an omission, but instead indicates recognition that the amount of silicon in a steel can often be traced directly to the deoxidation practice employed in making it.

Rimmed and capped steels are not deoxidized; the only silicon present is the residual amount left from scrap or raw materials, typically less than 0.05% Si. Specifications and orders for these steels customarily indicate that the steel must be made rimmed or capped, as required by the purchaser; restrictions on silicon content are not usually given.

The extent of rimming action during the solidification of semikilled steel ingots must be carefully controlled by matching the amount of deoxidizer with the oxygen content of the molten steel. The amount of silicon required for deoxidation can vary from heat to heat. Thus, the silicon content of the solid metal can also vary slightly from heat to heat. A maximum silicon content of 0.10% is sometimes specified for semikilled steel, but this requirement is not very restrictive; for certain heats, a silicon addition sufficient to leave a residue of 0.10% can be enough of an addition to kill the steel.

Killed steels are fully deoxidized during their manufacture; deoxidation can be accomplished by additions of silicon, aluminum, or both, or by vacuum treatment of the molten steel. Because it is the least costly of these methods, silicon deoxidation is frequently used. For silicon-killed steels, a range of 0.15 to 0.30% Si is often specified, providing the manufacturer with adequate flexibility to compensate for variations in the steelmaking process and ensuring a steel acceptable for most applications. Aluminum-killed or vacuum-deoxidized steels require no silicon; a requirement for minimum silicon content in such steel is unnecessary. A maximum permissible silicon content is appropriate for all killed plain carbon steels; a minimum silicon content implies a restriction that the steel must be silicon killed. Silicon is intentionally added to some alloy steels, for which it serves as both a deoxidizer and an alloying element to modify the properties of the steel. An acceptable range of silicon content would be appropriate for these steels.

Users and specifiers of steel mill products must realize that the silicon content of these items cannot be established independently of deoxidation practice. In ordering mill products, it is often desirable to cite a standard specification (such as an ASTM specification) where the various ramifications of restrictions on silicon content have already been considered in preparing the specification. In some instances, such as the forming of low-carbon steel sheet, the choice of deoxidation practice can significantly affect the performance of the steel; in such cases, it is appropriate to specify the desired practice.

SAE-AISI Designations

As stated above, the most widely used system for designating carbon and alloy steels is the SAE-AISI system. Technically, there are two separate systems, but they are nearly identical and have been carefully coordinated by the two groups. It should be noted, however, that AISI has discontinued the practice of designating steels. Therefore, the reader should consult Volume 1, *Materials,* of the *SAE Handbook* for the most up-to-date information.

The SAE-AISI system is applied to semi-finished forgings, hot-rolled and cold-finished bars, wire rod and seamless tubular goods, structural shapes, plates, sheet, strip, and welded tubing. Table 9 summarizes the numerical designations used in both SAE and AISI. The fact that a particular steel is listed by SAE or AISI implies only that it has been produced in appreciable quantity. It does not imply that other grades are unavailable, nor that any particular steel producer makes all of the listed grades.

Table 9 SAE-AISI system of designations for carbon and alloy steels

Numerals and digits	**Type of steel and nominal alloy content, %**
Carbon steels	
10*xx*[(a)]	Plain carbon (Mn 1.00 max)
11*xx*	Resulfurized
12*xx*	Resulfurized and rephosphorized

15*xx*	Plain carbon (max Mn range: 1.00-1.65)
Manganese steels	
13*xx*	Mn 1.75
Nickel steels	
23*xx*	Ni 3.50
25*xx*	Ni 5.00
Nickel-chromium steels	
31*xx*	Ni 1.25; Cr 0.65 and 0.80
32*xx*	Ni 1.75; Cr 1.07
33*xx*	Ni 3.50; Cr 1.50 and 1.57
34*xx*	Ni 3.00; Cr 0.77
Molybdenum steels	
40*xx*	Mo 0.20 and 0.25
44*xx*	Mo 0.40 and 0.52
Chromium-molybdenum steels	
41*xx*	Cr 0.50, 0.80, and 0.95; Mo 0.12, 0.20, 0.25, and 0.30
Nickel-chromium-molybdenum steels	
43*xx*	Ni 1.82; Cr 0.50 and 0.80; Mo 0.25
43BV*xx*	Ni 1.82; Cr 0.50; Mo 0.12 and 0.25; V 0.03 min
47*xx*	Ni 1.05; Cr 0.45; Mo 0.20 and 0.35
81*xx*	Ni 0.30; Cr 0.40; Mo 0.12

86*xx*	Ni 0.55; Cr 0.50; Mo 0.20
87*xx*	Ni 0.55; Cr 0.50; Mo 0.25
88*xx*	Ni 0.55; Cr 0.50; Mo 0.35
93*xx*	Ni 3.25; Cr 1.20; Mo 0.12
94*xx*	Ni 0.45; Cr 0.40; Mo 0.12
97*xx*	Ni 0.55; Cr 0.20; Mo 0.20
98*xx*	Ni 1.00; Cr 0.80; Mo 0.25
Nickel-molybdenum steels	
46*xx*	Ni 0.85 and 1.82; Mo 0.20 and 0.25
48*xx*	Ni 3.50; Mo 0.25
Chromium steels	
50*xx*	Cr 0.27, 0.40, 0.50, and 0.65
51*xx*	Cr 0.80, 0.87, 0.92, 0.95, 1.00, and 1.05
50*xxx*	Cr 0.50; C 1.00 min
51*xxx*	Cr 1.02; C 1.00 min
52*xxx*	Cr 1.45; C 1.00 min
Chromium-vanadium steels	
61*xx*	Cr 0.60, 0.80, and 0.95; V 0.10 and 0.15 min
Tungsten-chromium steel	
72*xx*	W 1.75; Cr 0.75
Silicon-manganese steels	

92*xx*	Si 1.40 and 2.00; Mn 0.65, 0.82, and 0.85; Cr 0 and 0.65
Boron steels	
*xx*B*xx*	B denotes boron steel
Leaded steels	
*xx*L*xx*	L denotes leaded steel
Vanadium steels	
*xx*V*xx*	V denotes vanadium steel

(a) The *xx* in the last two digits of these designations indicates that the carbon content (in hundredths of a percent) is to be inserted.

SAE-AISI Designations for Carbon Steels

As shown in Table 9, carbon steels comprise the l*xxx* groups in the SAE-AISI system and are subdivided into four distinct series as a result of the differences in certain fundamental properties among them.

Plain carbon steels (1.00% max Mn) in the 10*xx* group are listed in Tables 10 and 11; note that ranges and limits of chemical composition depend on the product form. Designations for merchant quality steels, given in Table 12, include the prefix M. A carbon steel designation with the letter B inserted between the second and third digits indicates the steel contains 0.0005 to 0.003% B. Likewise, the letter L inserted between the second and third digits indicates that the steel contains 0.15 to 0.35% Pb for enhanced machinability.

Table 10 Carbon steel compositions

Applicable to semifinished products for forging, hot-rolled and cold-finished bars, wire rods, and seamless tubing

Designation		**Cast or heat chemical ranges and limits[(a)], %**			
UNS No.	**SAE-AISI No.**	**C**	**Mn**	**P max**	**S max**
G10050	1005	0.06 max	0.35 max	0.040	0.050
G10060	1006	0.08 max	0.25-0.40	0.040	0.050
G10080	1008	0.10 max	0.30-0.50	0.040	0.050
G10100	1010	0.08-0.13	0.30-0.60	0.040	0.050
G10120	1012	0.10-0.15	0.30-0.60	0.040	0.050

G10130	1013	0.11-0.16	0.50-0.80	0.040	0.050
G10150	1015	0.13-0.18	0.30-0.60	0.040	0.050
G10160	1016	0.13-0.18	0.60-0.90	0.040	0.050
G10170	1017	0.15-0.20	0.30-0.60	0.040	0.050
G10180	1018	0.15-0.20	0.60-0.90	0.040	0.050
G10190	1019	0.15-0.20	0.70-1.00	0.040	0.050
G10200	1020	0.18-0.23	0.30-0.60	0.040	0.050
G10210	1021	0.18-0.23	0.60-0.90	0.040	0.050
G10220	1022	0.18-0.23	0.70-1.00	0.040	0.050
G10230	1023	0.20-0.25	0.30-0.60	0.040	0.050
G10250	1025	0.22-0.28	0.30-0.60	0.040	0.050
G10260	1026	0.22-0.28	0.60-0.90	0.040	0.050
G10290	1029	0.25-0.31	0.60-0.90	0.040	0.050
G10300	1030	0.28-0.34	0.60-0.90	0.040	0.050
G10350	1035	0.32-0.38	0.60-0.90	0.040	0.050
G10370	1037	0.32-0.38	0.70-1.00	0.040	0.050
G10380	1038	0.35-0.42	0.60-0.90	0.040	0.050
G10390	1039	0.37-0.44	0.70-1.00	0.040	0.050
G10400	1040	0.37-0.44	0.60-0.90	0.040	0.050
G10420	1042	0.40-0.47	0.60-0.90	0.040	0.050
G10430	1043	0.40-0.47	0.70-1.00	0.040	0.050

G10440	1044	0.43-0.50	0.30-0.60	0.040	0.050
G10450	1045	0.43-0.50	0.60-0.90	0.040	0.050
G10460	1046	0.43-0.50	0.70-1.00	0.040	0.050
G10490	1049	0.46-0.53	0.60-0.90	0.040	0.050
G10500	1050	0.48-0.55	0.60-0.90	0.040	0.050
G10530	1053	0.48-0.55	0.70-1.00	0.040	0.050
G10550	1055	0.50-0.60	0.60-0.90	0.040	0.050
G10590	1059	0.55-0.65	0.50-0.80	0.040	0.050
G10600	1060	0.55-0.65	0.60-0.90	0.040	0.050
G10640	1064	0.60-0.70	0.50-0.80	0.040	0.050
G10650	1065	0.60-0.70	0.60-0.90	0.040	0.050
G10690	1069	0.65-0.75	0.40-0.70	0.040	0.050
G10700	1070	0.65-0.75	0.60-0.90	0.040	0.050
G10740	1074	0.70-0.80	0.50-0.80	0.040	0.050
G10750	1075	0.70-0.80	0.40-0.70	0.040	0.050
G10780	1078	0.72-0.85	0.30-0.60	0.040	0.050
G10800	1080	0.75-0.88	0.60-0.90	0.040	0.050
G10840	1084	0.80-0.93	0.60-0.90	0.040	0.050
G10850	1085	0.80-0.93	0.70-1.00	0.040	0.050
G10860	1086	0.80-0.93	0.30-0.50	0.040	0.050
G10900	1090	0.85-0.98	0.60-0.90	0.040	0.050

G10950	1095	0.90-1.03	0.30-0.50	0.040	0.050

(a) When silicon ranges or limits are required for bar and semifinished products, the following ranges are commonly used: 0.10% max; 0.10 to 0.20%; 0.15 to 0.35%; 0.20 to 0.40%; or 0.30-0.60%. For rods, the following ranges are commonly used: 0.10 max; 0.07-0.15%; 0.10-0.20%; 0.15-0.35%; 0.20-0.40%; and 0.30-0.60%. Steels listed in this table can be produced with additions of lead or boron. Leaded steels typically contain 0.15-0.35% Pb and are identified by inserting the letter L in the designation (10L45); boron steels can be expected to contain 0.0005-0.003% B and are identified by inserting the letter B in the designation (10B46).

Table 11 Carbon steel compositions

Applicable only to structural shapes, plates, strip, sheets, and welded tubing

Designation		**Cast or heat chemical ranges and limits[(a)], %**			
UNS No.	**SAE-AISI No.**	**C**	**Mn**	**P max**	**S max**
G10060	1006	0.08 max	0.45 max	0.040	0.050
G10080	1008	0.10 max	0.50 max	0.040	0.050
G10090	1009	0.15 max	0.60 max	0.040	0.050
G10100	1010	0.08-0.13	0.30-0.60	0.040	0.050
G10120	1012	0.10-0.15	0.30-0.60	0.040	0.050
G10150	1015	0.12-0.18	0.30-0.60	0.040	0.050
G10160	1016	0.12-0.18	0.60-0.90	0.040	0.050
G10170	1017	0.14-0.20	0.30-0.60	0.040	0.050
G10180	1018	0.14-0.20	0.60-0.90	0.040	0.050
G10190	1019	0.14-0.20	0.70-1.00	0.040	0.050
G10200	1020	0.17-0.23	0.30-0.60	0.040	0.050
G10210	1021	0.17-0.23	0.60-0.90	0.040	0.050
G10220	1022	0.17-0.23	0.70-1.00	0.040	0.050
G10230	1023	0.19-0.25	0.30-0.60	0.040	0.050

G10250	1025	0.22-0.28	0.30-0.60	0.040	0.050
G10260	1026	0.22-0.28	0.60-0.90	0.040	0.050
G10300	1030	0.27-0.34	0.60-0.90	0.040	0.050
G10330	1033	0.29-0.36	0.70-1.00	0.040	0.050
G10350	1035	0.31-0.38	0.60-0.90	0.040	0.050
G10370	1037	0.31-0.38	0.70-1.00	0.040	0.050
G10380	1038	0.34-0.42	0.60-0.90	0.040	0.050
G10390	1039	0.36-0.44	0.70-1.00	0.040	0.050
G10400	1040	0.36-0.44	0.60-0.90	0.040	0.050
G10420	1042	0.39-0.47	0.60-9.90	0.040	0.050
G10430	1043	0.39-0.47	0.70-1.00	0.040	0.050
G10450	1045	0.42-0.50	0.60-0.90	0.040	0.050
G10460	1046	0.42-0.50	0.70-1.00	0.040	0.050
G10490	1049	0.45-0.53	0.60-0.90	0.040	0.050
G10500	1050	0.47-0.55	0.60-0.90	0.040	0.050
G10550	1055	0.52-0.60	0.60-0.90	0.040	0.050
G10600	1060	0.55-0.66	0.60-0.90	0.040	0.050
G10640	1064	0.59-0.70	0.50-0.80	0.040	0.050
G10650	1065	0.59-0.70	0.60-0.90	0.040	0.050
G10700	1070	0.65-0.76	0.60-0.90	0.040	0.050
G10740	1074	0.69-0.80	0.50-0.80	0.040	0.050

G10750	1075	0.69-0.80	0.40-0.70	0.040	0.050
G10780	1078	0.72-0.86	0.30-0.60	0.040	0.050
G10800	1080	0.74-0.88	0.60-0.90	0.040	0.050
G10840	1084	0.80-0.94	0.60-0.90	0.040	0.050
G10850	1085	0.80-0.94	0.70-1.00	0.040	0.050
G10860	1086	0.80-0.94	0.30-0.50	0.040	0.050
G10900	1090	0.84-0.98	0.60-0.90	0.040	0.050
G10950	1095	0.90-1.04	0.30-0.50	0.040	0.050

(a) When silicon ranges or limits are required, the following ranges and limits are commonly used: up to SAE 1025 inclusive, 0.10% max, 0.10-0.25%, or 0.15-0.35%. Over SAE 1025, 0.10-0.25% or 0.15-0.35%.

Table 12 Composition ranges and limits for merchant quality steels

SAE-AISI No.	**Cast or heat chemical ranges and limits(a), %**			
	C	**Mn**	**P max**	**S max**
M1008	0.10 max	0.25-0.60	0.04	0.05
M1010	0.07-0.14	0.25-0.60	0.04	0.05
M1012	0.09-0.16	0.25-0.60	0.04	0.05
M1015	0.12-0.19	0.25-0.60	0.04	0.05
M1017	0.14-0.21	0.25-0.60	0.04	0.05
M1020	0.17-0.24	0.25-0.60	0.04	0.05
M1023	0.19-0.27	0.25-0.60	0.04	0.05
M1025	0.20-0.30	0.25-0.60	0.04	0.05

M1031	0.26-0.36	0.25-0.60	0.04	0.05
M1044	0.40-0.50	0.25-0.60	0.04	0.05

(a) Merchant quality steel bars are not produced to any specified silicon content.

Free-Machining Grades. Resulfurized carbon steels in the 11*xx* group are listed in Table 13, and resulfurized and rephosphorized carbon steels in the 12*xx* group are listed in Table 14. Both of these groups of steels are produced for applications requiring good machinability.

Table 13 Free-machining (resulfurized) carbon steel compositions

Applicable to semifinished products for forging, hot-rolled and cold-finished bars, wire rods, and seamless tubing

Designation		**Cast or heat chemical ranges and limits(a), %**			
UNS No.	**SAE-AISI No.**	**C**	**Mn**	**P max**	**S**
G11080	1108	0.08-0.13	0.50-0.80	0.040	0.08-0.13
G11100	1110	0.08-0.13	0.30-0.60	0.040	0.08-0.13
G11170	1117	0.14-0.20	1.00-1.30	0.040	0.08-0.13
G11180	1118	0.14-0.20	1.30-1.60	0.040	0.08-0.13
G11370	1137	0.32-0.39	1.35-1.65	0.040	0.08-0.13
G11390	1139	0.35-0.43	1.35-1.65	0.040	0.13-0.20
G11400	1140	0.37-0.44	0.70-1.00	0.040	0.08-0.13
G11410	1141	0.37-0.45	1.35-1.65	0.040	0.08-0.13
G11440	1144	0.40-0.48	1.35-1.65	0.040	0.24-0.33
G11460	1146	0.42-0.49	0.70-1.00	0.040	0.08-0.13
G11510	1151	0.48-0.55	0.70-1.00	0.040	0.08-0.13

(a) When lead ranges or limits are required, or when silicon ranges or limits are required for bars or semifinished products, the values in Table 10 apply. For rods, the following ranges and limits for silicon are commonly used: up to SAE 1110 inclusive, 0.10% max; SAE 1117 and over, 0.10% max, 0.10-0.20%, or 0.15-0.35%.

Table 14 Free-machining (rephosphorized and resulfurized) carbon steel compositions

Applicable to semifinished products for forging, hot-rolled and cold-finished bars, wire rods, and seamless tubing

Designation		**Cast or heat chemical ranges and limits**[(a)]**, %**				
UNS No.	**SAE-AISI No.**	**C max**	**Mn**	**P**	**S**	**Pb**
G12110	1211	0.13	0.60-0.90	0.07-0.12	0.10-0.15	. . .
G12120	1212	0.13	0.70-1.00	0.07-0.12	0.16-0.23	. . .
G12130	1213	0.13	0.70-1.00	0.07-0.12	0.24-0.33	. . .
G12150	1215	0.09	0.75-1.05	0.04-0.09	0.26-0.35	. . .
G12144	12L14	0.15	0.85-1.15	0.04-0.09	0.26-0.35	0.15-0.35

(a) When lead ranges or limits are required, the values in Table 10 apply. It is not common practice to produce the 12*xx* series of steels to specified limits for silicon because of its adverse effect on machinability.

Plain-Carbon Steels (1.0 to 1.65% Mn). Tables 15 and 16 list steels having nominal manganese content of between 0.9 and 1.5% but no other alloying additions; these steels now have 15*xx* designations in place of the 10*xx* designations formerly used.

Table 15 High-manganese carbon steel compositions

Applicable only to semifinished products for forging, hot-rolled and cold-finished bars, wire rods, and seamless tubing

Designation		**Cast or heat chemical ranges and limits**[(a)]**, %**			
UNS No.	**SAE-AISI No.**	**C**	**Mn**	**P max**	**S max**
G15130	1513	0.10-0.16	1.10-1.40	0.040	0.050
G15220	1522	0.18-0.24	1.10-1.40	0.040	0.050
G15240	1524	0.19-0.25	1.35-1.65	0.040	0.050
G15260	1526	0.22-0.29	1.10-1.40	0.040	0.050
G15270	1527	0.22-0.29	1.20-1.50	0.040	0.050

G15360	1536	0.30-0.37	1.20-1.50	0.040	0.050
G15410	1541	0.36-0.44	1.35-1.65	0.040	0.050
G15480	1548	0.44-0.52	1.10-1.40	0.040	0.050
G15510	1551	0.45-0.56	0.85-1.15	0.040	0.050
G15520	1552	0.47-0.55	1.20-1.50	0.040	0.050
G15610	1561	0.55-0.65	0.75-1.05	0.040	0.050
G15660	1566	0.60-0.71	0.85-1.15	0.040	0.050

(a) When silicon, lead, and boron ranges or limits are required, the values in Table 10 apply.

Table 16 High-manganese carbon steel compositions

Applicable only to structural shapes, plates, strip, sheets, and welded tubing

Designation		**Cast or heat chemical ranges and limits[(a)], %**				**Former SAE number**
UNS No.	**SAE-AISI No.**	**C max**	**Mn**	**P max**	**S max**	
G15240	1524	0.18-0.25	1.30-1.65	0.040	0.050	1024
G15270	1527	0.22-0.29	1.20-1.55	0.040	0.050	1027
G15360	1536	0.30-0.38	1.20-1.55	0.040	0.050	1036
G15410	1541	0.36-0.45	1.30-1.65	0.040	0.050	1041
G15480	1548	0.43-0.52	1.05-1.40	0.040	0.050	1048
G15520	1552	0.46-0.55	1.20-1.55	0.040	0.050	1052

(a) When silicon ranges or limits are required, the values shown in Table 11 apply.

H-Steels. Certain steels have hardenability requirements in addition to the limits and ranges of chemical composition. They are distinguished from similar grades that have no hardenability requirements by the use of the suffix H (Table 17). Hardenability bands for the steels listed in Table 17 can be found in SAE J1268.

Table 17 Composition of carbon and carbon-boron H-steels

UNS No.	SAE or AISI No.	Ladle chemical composition, wt%				
		C	**Mn**	**Si**	**P, maximum[(a)]**	**S, maximum[(a)]**
H10380	1038H	0.34-0.43	0.50-1.00	0.15-0.35	0.040	0.050
H10450	1045H	0.42-0.51	0.50-1.00	0.15-0.35	0.040	0.050
H15220	1522H	0.17-0.25	1.00-1.50	0.15-0.35	0.040	0.050
H15240	1524H	0.18-0.26	1.25-1.75	0.15-0.35	0.040	0.050
H15260	1526H	0.21-0.30	1.00-1.50	0.15-0.35	0.040	0.050
H15410	1541H	0.35-0.45	1.25-1.75	0.15-0.35	0.040	0.050
H15211	15B21H(b)	0.17-0.24	0.70-1.20	0.15-0.35	0.040	0.050
H15281	15B28H(b)	0.25-0.34	1.00-1.50	0.15-0.35	0.040	0.050
H15301	15B30H(b)	0.27-0.35	0.70-1.20	0.15-0.35	0.040	0.050
H15351	15B35H(b)	0.31-0.39	0.70-1.20	0.15-0.35	0.040	0.050
H15371	15B37H(b)	0.30-0.39	1.00-1.50	0.15-0.35	0.040	0.050
H15411	15B41H(b)	0.35-0.45	1.25-1.75	0.15-0.35	0.040	0.050
H15481	15B48H(b)	0.43-0.53	1.00-1.50	0.15-0.35	0.040	0.050

(a) If electric furnace practice is specified or required, the limit for both phosphorus and sulfur is 0.025%, and the prefix E is added to the SAE or AISI number.

(b) These steels contain 0.005 to 0.003% B.

SAE-AISI Designations for Alloy Steels

Using the SAE-AISI designation system, a steel is considered an alloy steel when the maximum content range of alloying elements exceeds one or more of the following limits: 1.65% Mn, 0.60% Si, or 0.60% Cu. Also included in the recognized field of alloy steels are steels with a specified or required range or minimum quantity of the following elements: aluminum, boron, chromium (up to 3.99%), cobalt, niobium, molybdenum, nickel, titanium, tungsten, vanadium, zirconium, or any other alloying element added to increase hardenability in order to optimize mechanical properties and toughness after heat treatment. In some cases, however, alloy additions are used to reduce environmental degradation under certain specified service conditions. In general, total alloy content for SAE-AISI constructional steels does not exceed 5%.

Alloy sheet and strip are available as hot-rolled and cold-rolled steel in coils and cut lengths. Other product forms of alloy steel covered by SAE-AISI designations include hot-rolled plate and hot-rolled, cold-rolled, and cold-drawn bar, rod, and wire.

In the SAE-AISI system of designations, the major alloying elements in an alloy steel are indicated by the first two digits of the designation (Table 9). The amount of carbon, in hundredths of a percent, is indicated by the last two (or three) digits. The chemical compositions of SAE-AISI standard grades of alloy steels are given in Tables 18 and 19. For alloy steels that have specific hardenability requirements, the suffix H is used to distinguish these steels from corresponding grades that have no hardenability requirement (Table 20). Corresponding hardenability bands for these steels is described in SAE J1268. As with carbon steels, the letter B inserted between the second and third digits indicates that the steel contains boron. The prefix E signifies that the steel was produced by the electric furnace process.

Table 18 Alloy steel compositions applicable to billets, blooms, slabs, and hot-rolled and cold-finished bars

Designation			**Ladle chemical composition limits[(a)], %**								
UNS No.	**SAE No.**	**Corresponding AISI No.**	**C**	**Mn**	**P**	**S**	**Si**	**Ni**	**Cr**	**Mo**	**V**
G13300	1330	1330	0.28-0.33	1.60-1.90	0.035	0.040	0.15-0.35	. . .	. . .	. . .	. . .
G13350	1335	1335	0.33-0.38	1.60-1.90	0.035	0.040	0.15-0.35	. . .	. . .	. . .	. . .
G13400	1340	1340	0.38-0.43	1.60-1.90	0.035	0.040	0.15-0.35	. . .	. . .	. . .	. . .
G13450	1345	1345	0.43-0.48	1.60-1.90	0.035	0.040	0.15-0.35	. . .	. . .	. . .	. . .
G40230	4023	4023	0.20-0.25	0.70-0.90	0.035	0.040	0.15-0.35	. . .	. . .	. . .	. . .
G40240	4024	4024	0.20-0.25	0.70-0.90	0.035	0.035-0.050	0.15-0.35	. . .	. . .	0.20-0.30	. . .
G40270	4027	4027	0.25-0.30	0.70-0.90	0.035	0.040	0.15-0.35	. . .	. . .	0.20-0.30	. . .
G40280	4028	4028	0.25-0.30	0.70-0.90	0.035	0.035-0.050	0.15-0.35	. . .	. . .	0.20-0.30	. . .
G40320	4032	. . .	0.30-0.35	0.70-0.90	0.035	0.040	0.15-0.35	. . .	. . .	0.20-0.30	. . .

G40370	4037	4037	0.35-0.40	0.70-0.90	0.035	0.040	0.15-0.35	. . .	. . .	0.20-0.30	. . .
G40420	4042	. . .	0.40-0.45	0.70-0.90	0.035	0.040	0.15-0.35	. . .	. . .	0.20-0.30	. . .
G40470	4047	4047	0.45-0.50	0.70-0.90	0.035	0.040	0.15-0.35	. . .	. . .	0.20-0.30	. . .
G41180	4118	4118	0.18-0.23	0.70-0.90	0.035	0.040	0.15-0.35	. . .	0.40-0.60	0.08-0.15	. . .
G41300	4130	4130	0.28-0.33	0.40-0.60	0.035	0.040	0.15-0.35	. . .	0.80-1.10	0.15-0.25	. . .
G41350	4135	. . .	0.33-0.38	0.70-0.90	0.035	0.040	0.15-0.35	. . .	0.80-1.10	0.15-0.25	. . .
G41370	4137	4137	0.35-0.40	0.70-0.90	0.035	0.040	0.15-0.35	. . .	0.80-1.10	0.15-0.25	. . .
G41400	4140	4140	0.38-0.43	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.80-1.10	0.15-0.25	. . .
G41420	4142	4142	0.40-0.45	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.80-1.10	0.15-0.25	. . .
G41450	4145	4145	0.41-0.48	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.80-1.10	0.15-0.25	. . .
G41470	4147	4147	0.45-0.50	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.80-1.10	0.15-0.25	. . .
G41500	4150	4150	0.48-0.53	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.80-1.10	0.15-0.25	. . .
G41610	4161	4161	0.56-0.64	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.70-0.90	0.25-0.35	. . .
G43200	4320	4320	0.17-0.22	0.45-0.65	0.035	0.040	0.15-0.35	1.65-2.00	0.40-0.60	0.20-0.30	. . .
G43400	4340	4340	0.38-0.43	0.60-0.80	0.035	0.040	0.15-0.35	1.65-2.00	0.70-0.90	0.20-0.30	. . .
G43406	E4340(b)	E4340	0.38-0.43	0.65-0.85	0.025	0.025	0.15-0.35	1.65-2.00	0.70-0.90	0.20-0.30	. . .

G44220	4422	. . .	0.20-0.25	0.70-0.90	0.035	0.040	0.15-0.35	. . .	. . .	0.35-0.45	. . .
G44270	4427	. . .	0.24-0.29	0.70-0.90	0.035	0.040	0.15-0.35	. . .	. . .	0.35-0.45	. . .
G46150	4615	4615	0.13-0.18	0.45-0.65	0.035	0.040	0.15-0.25	1.65-2.00	. . .	0.20-0.30	. . .
G46170	4617	. . .	0.15-0.20	0.45-0.65	0.035	0.040	0.15-0.35	1.65-2.00	. . .	0.20-0.30	. . .
G46200	4620	4620	0.17-0.22	0.45-0.65	0.035	0.040	0.15-0.35	1.65-2.00	. . .	0.20-0.30	. . .
G46260	4626	4626	0.24-0.29	0.45-0.65	0.035	0.04 max	0.15-0.35	0.70-1.00	. . .	0.15-0.25	. . .
G47180	4718	4718	0.16-0.21	0.70-0.90	. . .	. . .	. . .	0.90-1.20	0.35-0.55	0.30-0.40	. . .
G47200	4720	4720	0.17-0.22	0.50-0.70	0.035	0.040	0.15-0.35	0.90-1.20	0.35-0.55	0.15-0.25	. . .
G48150	4815	4815	0.13-0.18	0.40-0.60	0.035	0.040	0.15-0.35	3.25-3.75	. . .	0.20-0.30	. . .
G48170	4817	4817	0.15-0.20	0.40-0.60	0.035	0.040	0.15-0.35	3.25-3.75	. . .	0.20-0.30	. . .
G48200	4820	4820	0.18-0.23	0.50-0.70	0.035	0.040	0.15-0.35	3.25-3.75	. . .	0.20-0.30	. . .
G50401	50B40(c)	. . .	0.38-0.43	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.40-0.60	. . .	. . .
G50441	50B44(c)	50B44	0.43-0.48	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.40-0.60	. . .	. . .
G50460	5046	. . .	0.43-0.48	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.20-0.35	. . .	. . .
G50461	50B46(c)	50B46	0.44-0.49	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.20-0.35	. . .	. . .
G50501	50B50(c)	50B50	0.48-0.53	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.40-0.60	. . .	. . .

G50600	5060	. . .	0.56-0.64	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.40-0.60	. . .	. . .
G50601	50B60(c)	50B60	0.56-0.64	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.40-0.60	. . .	. . .
G51150	5115	. . .	0.13-0.18	0.70-0.90	0.035	0.040	0.15-0.35	. . .	0.70-0.90	. . .	. . .
G51170	5117	5117	0.15-0.20	0.70-0.90	0.040	0.040	0.15-0.35	. . .	0.70-0.90	. . .	. . .
G51200	5120	5120	0.17-0.22	0.70-0.90	0.035	0.040	0.15-0.35	. . .	0.70-0.90	. . .	. . .
G51300	5130	5130	0.28-0.33	0.70-0.90	0.035	0.040	0.15-0.35	. . .	0.80-1.10	. . .	. . .
G51320	5132	5132	0.30-0.35	0.60-0.80	0.035	0.040	0.15-0.35	. . .	0.75-1.00	. . .	. . .
G51350	5135	5135	0.33-0.38	0.60-0.80	0.035	0.040	0.15-0.35	. . .	0.80-1.05	. . .	. . .
G51400	5140	5140	0.38-0.43	0.70-0.90	0.035	0.040	0.15-0.35	. . .	0.70-0.90	. . .	. . .
G51470	5147	5147	0.46-0.51	0.70-0.95	0.035	0.040	0.15-0.35	. . .	0.85-1.15	. . .	. . .
G51500	5150	5150	0.48-0.53	0.70-0.90	0.035	0.040	0.15-0.35	. . .	0.70-0.90	. . .	. . .
G51550	5155	5155	0.51-0.59	0.70-0.90	0.035	0.040	0.15-0.35	. . .	0.70-0.90	. . .	. . .
G51600	5160	5160	0.56-0.64	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.70-0.90	. . .	. . .
G51601	51B60(c)	51B60	0.56-0.64	0.75-1.00	0.035	0.040	0.15-0.35	. . .	0.70-0.90	. . .	. . .
G50986	50100(b)	. . .	0.98-1.10	0.25-0.45	0.025	0.025	0.15-0.35	. . .	0.40-0.60	. . .	. . .
G51986	51100(b)	E51100	0.98-1.10	0.25-0.45	0.025	0.025	0.15-0.35	. . .	0.90-1.15	. . .	. . .

G52986	52100(b)	E52100	0.98-1.10	0.25-0.45	0.025	0.025	0.15-0.35	. . .	1.30-1.60	. . .	. . .
G61180	6118	6118	0.16-0.21	0.50-0.70	0.035	0.040	0.15-0.35	. . .	0.50-0.70	. . .	0.10-0.15
G61500	6150	6150	0.48-0.53	0.70-0.90	0.035	0.040	0.15-0.35	. . .	0.80-1.10	. . .	0.15 min
G81150	8115	8115	0.13-0.18	0.70-0.90	0.035	0.040	0.15-0.35	0.20-0.40	0.30-0.50	0.08-0.15	. . .
G81451	81B45(c)	81B45	0.43-0.48	0.75-1.00	0.035	0.040	0.15-0.35	0.20-0.40	0.35-0.55	0.08-0.15	. . .
G86150	8615	8615	0.13-0.18	0.70-0.90	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86170	8617	8617	0.15-0.20	0.70-0.90	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86200	8620	8620	0.18-0.23	0.70-0.90	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86220	8622	8622	0.20-0.25	0.70-0.90	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86250	8625	8625	0.23-0.28	0.70-0.90	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86270	8627	8627	0.25-0.30	0.70-0.90	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86300	8630	8630	0.28-0.33	0.70-0.90	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86370	8637	8637	0.35-0.40	0.75-1.00	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86400	8640	8640	0.38-0.43	0.75-1.00	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86420	8642	8642	0.40-0.45	0.75-1.00	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86450	8645	8645	0.43-0.48	0.75-1.00	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .

G86451	86B45[c]	. . .	0.43-0.48	0.75-1.00	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86500	8650	. . .	0.48-0.53	0.75-1.00	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86550	8655	8655	0.51-0.59	0.75-1.00	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G86600	8660	. . .	0.56-0.64	0.75-1.00	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.15-0.25	. . .
G87200	8720	8720	0.18-0.23	0.70-0.90	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.20-0.30	. . .
G87400	8740	8740	0.38-0.43	0.75-1.00	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.20-0.30	. . .
G88220	8822	8822	0.20-0.25	0.75-1.00	0.035	0.040	0.15-0.35	0.40-0.70	0.40-0.60	0.30-0.40	. . .
G92540	9254	. . .	0.51-0.59	0.60-0.80	0.035	0.040	1.20-1.60	. . .	0.60-0.80	. . .	. . .
G92600	9260	9260	0.56-0.64	0.75-1.00	0.035	0.040	1.80-2.20	. . .	. . .	. . .	. . .
G93106	9310[b]	. . .	0.08-0.13	0.45-0.65	0.025	0.025	0.15-0.35	3.00-3.50	1.00-1.40	0.08-0.15	. . .
G94151	94B15[c]	. . .	0.13-0.18	0.75-1.00	0.035	0.040	0.15-0.35	0.30-0.60	0.30-0.50	0.08-0.15	. . .
G94171	94B17[c]	94B17	0.15-0.20	0.75-1.00	0.035	0.040	0.15-0.35	0.30-0.60	0.30-0.50	0.08-0.15	. . .
G94301	94B30[c]	94B30	0.28-0.33	0.75-1.00	0.035	0.040	0.15-0.35	0.30-0.60	0.30-0.50	0.08-0.15	. . .

(a) Small quantities of certain elements that are not specified or required may be found in alloy steels. These elements are to be considered as incidental and are acceptable to the following maximum amount: copper to 0.35%, nickel to 0.25%, chromium to 0.20%, and molybdenum to 0.06%.

(b) Electric furnace steel.

(c) Boron content is 0.0005-0.003%.

Table 19 Composition ranges and limits for SAE-AISI standard alloy steel plate applicable for structural applications

Designation		**Heat composition ranges and limits[a], %**					
SAE-AISI	**UNS**	**C**	**Mn**	**Si[b]**	**Cr**	**Ni**	**Mo**
1330	G13300	0.27-0.34	1.50-1.90	0.15-0.30	. . .	. . .	. . .
1335	G13350	0.32-0.39	1.50-1.90	0.15-0.30	. . .	. . .	. . .
1340	G13400	0.36-0.44	1.50-1.90	0.15-0.30	. . .	. . .	. . .
1345	G13450	0.41-0.49	1.50-1.90	0.15-0.30	. . .	. . .	. . .
4118	G41180	0.17-0.23	0.60-0.90	0.15-0.30	0.40-0.65	. . .	0.08-0.15
4130	G41300	0.27-0.34	0.35-0.60	0.15-0.30	0.80-1.15	. . .	0.15-0.25
4135	G41350	0.32-0.39	0.65-0.95	0.15-0.30	0.80-1.15	. . .	0.15-0.25
4137	G41370	0.33-0.40	0.65-0.95	0.15-0.30	0.80-1.15	. . .	0.15-0.25
4140	G41400	0.36-0.44	0.70-1.00	0.15-0.30	0.80-1.15	. . .	0.15-0.25
4142	G41420	0.38-0.46	0.70-1.00	0.15-0.30	0.80-1.15	. . .	0.15-0.25
4145	G41450	0.41-0.49	0.70-1.00	0.15-0.30	0.80-1.15	. . .	0.15-0.25
4340	G43400	0.36-0.44	0.55-0.80	0.15-0.30	0.60-0.90	1.65-2.00	0.20-0.30
E4340[c]	G43406	0.37-0.44	0.60-0.85	0.15-0.30	0.65-0.90	1.65-2.00	0.20-0.30
4615	G46150	0.12-0.18	0.40-0.65	0.15-0.30	. . .	1.65-2.00	0.20-0.30
4617	G46170	0.15-0.21	0.40-0.65	0.15-0.30	. . .	1.65-2.00	0.20-0.30
4620	G46200	0.16-0.22	0.40-0.65	0.15-0.30	. . .	1.65-2.00	0.20-0.30
5160	G51600	0.54-0.65	0.70-1.00	0.15-0.30	0.60-0.90	. . .	. . .
6150[d]	G61500	0.46-0.54	0.60-0.90	0.15-0.30	0.80-1.15	. . .	. . .

8615	G86150	0.12-0.18	0.60-0.90	0.15-0.30	0.35-0.60	0.40-0.70	0.15-0.25
8617	G86170	0.15-0.21	0.60-0.90	0.15-0.30	0.35-0.60	0.40-0.70	0.15-0.25
8620	G86200	0.17-0.23	0.60-0.90	0.15-0.30	0.35-0.60	0.40-0.70	0.15-0.25
8622	G86220	0.19-0.25	0.60-0.90	0.15-0.30	0.35-0.60	0.40-0.70	0.15-0.25
8625	G86250	0.22-0.29	0.60-0.90	0.15-0.30	0.35-0.60	0.40-0.70	0.15-0.25
8627	G86270	0.24-0.31	0.60-0.90	0.15-0.30	0.35-0.60	0.40-0.70	0.15-0.25
8630	G86300	0.27-0.34	0.60-0.90	0.15-0.30	0.35-0.60	0.40-0.70	0.15-0.25
8637	G86370	0.33-0.40	0.70-1.00	0.15-0.30	0.35-0.60	0.40-0.70	0.15-0.25
8640	G86400	0.36-0.44	0.70-1.00	0.15-0.30	0.35-0.60	0.40-0.70	0.15-0.25
8655	G86550	0.49-0.60	0.70-1.00	0.15-0.30	0.35-0.60	0.40-0.70	0.15-0.25
8742	G87420	0.38-0.46	0.70-1.00	0.15-0.30	0.35-0.60	0.40-0.70	0.20-0.30

Boron or lead can be added to these compositions. Small quantities of certain elements not required may be found. These elements are to be considered incidental and are acceptable to the following maximum amounts: copper to 0.35%, nickel to 0.25%, chromium to 0.20%, and molybdenum to 0.06%.

(a) Indicated ranges and limits apply to steels made by the open hearth or basic oxygen processes; maximum content for phosphorus is 0.035% and for sulfur 0.040%. For steels made by the electric furnace process, the ranges and limits are reduced as follows: C to 0.01%; Mn to 0.05%; Cr to 0.05% (<1.25%), 0.10% (>1.25%); maximum content for either phosphorus or sulfur is 0.025%.

(b) Other silicon ranges may be negotiated. Silicon is available in ranges of 0.10-0.20%, 0.20-0.30%, and 0.35% maximum (when carbon deoxidized) when so specified by the purchaser.

(c) Prefix "E" indicates that the steel is made by the electric furnace process.

(d) Contains 0.15% V minimum

Table 20 Composition of standard alloy H-steels

H-steel		**Ladle chemical composition[(a)(b)], wt%**						
UNS No.	**SAE or AISI No.**	**C**	**Mn**	**Si**	**Ni**	**Cr**	**Mo**	**V**

H13300	1330H	0.27-0.33	1.45-2.05	0.15-0.35	. . .	. . .	. . .	. . .
H13350	1335H	0.32-0.38	1.45-2.05	0.15-0.35	. . .	. . .	. . .	. . .
H13400	1340H	0.37-0.44	1.45-2.05	0.15-0.35	. . .	. . .	. . .	. . .
H13450	1345H	0.42-0.49	1.45-2.05	0.15-0.35	. . .	. . .	. . .	. . .
H40270	4027H	0.24-0.30	0.60-1.00	0.15-0.35	. . .	. . .	0.20-0.30	. . .
H40280(c)	4028H(c)	0.24-0.30	0.60-1.00	0.15-0.35	. . .	. . .	0.20-0.30	. . .
H40320	4032H	0.29-0.35	0.60-1.00	0.15-0.35	. . .	. . .	0.20-0.30	. . .
H40370	4037H	0.34-0.41	0.60-1.00	0.15-0.35	. . .	. . .	0.20-0.30	. . .
H40420	4042H	0.39-0.46	0.60-1.00	0.15-0.35	. . .	. . .	0.20-0.30	. . .
H40470	4047H	0.44-0.51	0.60-1.00	0.15-0.35	. . .	. . .	0.20-0.30	. . .
H41180	4118H	0.17-0.23	0.60-1.00	0.15-0.35	. . .	0.30-0.70	0.08-0.15	. . .
H41300	4130H	0.27-0.33	0.30-0.70	0.15-0.35	. . .	0.75-1.20	0.15-0.25	. . .
H41350	4135H	0.32-0.38	0.60-1.00	0.15-0.35	. . .	0.75-1.20	0.15-0.25	. . .
H41370	4137H	0.34-0.41	0.60-1.00	0.15-0.35	. . .	0.75-1.20	0.15-0.25	. . .
H41400	4140H	0.37-0.44	0.65-1.10	0.15-0.35	. . .	0.75-1.20	0.15-0.25	. . .
H41420	4142H	0.39-0.46	0.65-1.10	0.15-0.35	. . .	0.75-1.20	0.15-0.25	. . .
H41450	4145H	0.42-0.49	0.65-1.10	0.15-0.35	. . .	0.75-1.20	0.15-0.25	. . .
H41470	4147H	0.44-0.51	0.65-1.10	0.15-0.35	. . .	0.75-1.20	0.15-0.25	. . .
H41500	4150H	0.47-0.54	0.65-1.10	0.15-0.35	. . .	0.75-1.20	0.15-0.25	. . .
H41610	4161H	0.55-0.65	0.65-1.10	0.15-0.35	. . .	0.65-0.95	0.25-0.35	. . .
H43200	4320H	0.17-0.23	0.40-0.70	0.15-0.35	1.55-2.00	0.35-0.65	0.20-0.30	. . .

H43400	4340H	0.37-0.44	0.55-0.90	0.15-0.35	1.55-2.00	0.65-0.95	0.20-0.30	. . .
H43406(d)	E4340H(d)	0.37-0.44	0.60-0.95	0.15-0.35	1.55-2.00	0.65-0.95	0.20-0.30	. . .
H46200	4620H	0.17-0.23	0.35-0.75	0.15-0.35	1.55-2.00	. . .	0.20-0.30	. . .
H47180	4718H	0.15-0.21	0.60-0.95	0.15-0.35	0.85-1.25	0.30-0.60	0.30-0.40	. . .
H47200	4720H	0.17-0.23	0.45-0.75	0.15-0.35	0.85-1.25	0.30-0.60	0.15-0.25	. . .
H48150	4815H	0.12-0.18	0.30-0.70	0.15-0.35	3.20-3.80	. . .	0.20-0.30	. . .
H48170	4817H	0.14-0.20	0.30-0.70	0.15-0.35	3.20-3.80	. . .	0.20-0.30	. . .
H48200	4820H	0.17-0.23	0.40-0.80	0.15-0.35	3.20-3.80	. . .	0.20-0.30	. . .
H50401(e)	50B40H(e)	0.37-0.44	0.65-1.10	0.15-0.35	. . .	0.30-0.70	. . .	. . .
H50441(e)	50B44H(e)	0.42-0.49	0.65-1.10	0.15-0.35	. . .	0.30-0.70	. . .	. . .
H50460	5046H	0.43-0.50	0.65-1.10	0.15-0.35	. . .	0.13-0.43	. . .	. . .
H50461(e)	50B46H(e)	0.43-0.50	0.65-1.10	0.15-0.35	. . .	0.13-0.43	. . .	. . .
H50501(e)	50B50H(e)	0.47-0.54	0.65-1.10	0.15-0.35	. . .	0.30-0.70	. . .	. . .
H50601(e)	50B60H(e)	0.55-0.65	0.65-1.10	0.15-0.35	. . .	0.30-0.70	. . .	. . .
H51200	5120H	0.17-0.23	0.60-1.00	0.15-0.35	. . .	0.60-1.00	. . .	. . .
H51300	5130H	0.27-0.33	0.60-1.10	0.15-0.35	. . .	0.75-1.20	. . .	. . .
H51320	5132H	0.29-0.35	0.50-0.90	0.15-0.35	. . .	0.65-1.10	. . .	. . .
H51350	5135H	0.32-0.38	0.50-0.90	0.15-0.35	. . .	0.70-1.15	. . .	. . .
H51400	5140H	0.37-0.44	0.60-1.00	0.15-0.35	. . .	0.60-1.00	. . .	. . .
H51470	5147H	0.45-0.52	0.60-1.05	0.15-0.35	. . .	0.80-1.25	. . .	. . .
H51500	5150H	0.47-0.54	0.60-1.00	0.15-0.35	. . .	0.60-1.00	. . .	. . .

H51550	5155H	0.50-0.60	0.60-1.00	0.15-0.35	. . .	0.60-1.00	. . .	. . .
H51600	5160H	0.55-0.65	0.65-1.10	0.15-0.35	. . .	0.60-1.00	. . .	. . .
H51601(e)	51B60H(e)	0.55-0.65	0.65-1.10	0.15-0.35	. . .	0.60-1.00	. . .	. . .
H61180	6118H	0.15-0.21	0.40-0.80	0.15-0.35	. . .	0.40-0.80	. . .	0.10-0.15
H61500	6150H	0.47-0.54	0.60-1.00	0.15-0.35	. . .	0.75-1.20	. . .	0.15
H81451(e)	81B4S5(e)	0.42-0.49	0.70-1.05	0.15-0.35	0.15-0.45	0.30-0.60	0.08-0.15	. . .
H86170	8617H	0.14-0.20	0.60-0.95	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86200	8620H	0.17-0.23	0.60-0.95	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86220	8622H	0.19-0.25	0.60-9.95	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86250	8625H	0.22-0.28	0.60-0.95	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86270	8627H	0.24-0.30	0.60-0.95	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86300	8630H	0.27-0.33	0.60-0.95	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86301(e)	86B30H(e)	0.27-0.33	0.60-0.95	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86370	8637H	0.34-0.41	0.70-1.05	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86400	8640H	0.37-0.44	0.70-1.05	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86420	8642H	0.39-0.46	0.70-1.05	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86450	8645H	0.42-0.49	0.70-1.05	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86451(e)	86B45H9(e)	0.42-0.49	0.70-1.05	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86500	8650H	0.47-0.54	0.70-1.05	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86550	8655H	0.50-0.60	0.70-1.05	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .
H86600	8660H	0.55-0.65	0.70-1.05	0.15-0.35	0.35-0.75	0.35-0.65	0.15-0.25	. . .

H87200	8720H	0.17-0.23	0.60-0.95	0.15-0.35	0.35-0.75	0.35-0.65	0.20-0.30	. . .
H87400	8740H	0.37-0.44	0.70-1.05	0.15-0.35	0.35-0.75	0.35-0.65	0.20-0.30	. . .
H88220	8822H	0.19-0.25	0.70-1.05	0.15-0.35	0.35-0.75	0.35-0.65	0.30-0.40	. . .
H92600	9260H	0.55-0.65	0.65-1.10	1.70-2.20	. . .	. . .	. . .	. . .
H93100(d)	9310H(d)	0.07-0.13	0.40-0.70	0.15-0.35	2.95-3.55	1.00-1.45	0.08-0.15	. . .
H94151(e)	94B15H(e)	0.12-0.18	0.70-1.05	0.15-0.35	0.25-0.65	0.25-0.55	0.08-0.15	. . .
H94171(e)	94B17H(e)	0.14-0.20	0.70-1.05	0.15-0.35	0.25-0.65	0.25-0.55	0.08-0.15	. . .
H94301(e)	94B30H(e)	0.27-0.33	0.70-1.05	0.15-0.35	0.25-0.65	0.25-0.55	0.08-0.15	. . .

(a) Small quantities of certain elements may be found in alloy steel that are not specified or required. These elements are to be considered incidental and acceptable to the following maximum amounts: copper to 0.35%, nickel to 0.25%, chromium to 0.20%, and molybdenum to 0.06%.

(b) For open hearth and basic oxygen steels, maximum sulfur content is to be 0.040%, and maximum phosphorus content is to be 0.035%. Maximum phosphorus and sulfur in basic electric furnace steels are to be 0.025% each.

(c) Sulfur content range is 0.035-0.050%.

(d) Electric furnace steel.

(e) These steels contain 0.0005 to 0.003% B.

SAE-AISI Designations for High-Strength Steel Sheet

Both SAE and AISI have developed designation systems for high-strength sheet steels (including both structural carbon and HSLA grades). Using these systems, a high-strength steel is defined as a sheet product having a minimum specified yield strength of 240 MPa (35 ksi), without regard to the chemical composition or processing used to achieve that strength level. Excepted from these classification systems are alloy steels and stainless steels. Table 21 compares the SAE and AISI systems.

Table 21 Comparison of the SAE and AISI designation systems for high-strength sheet steel

Attribute	**SAE**	**AISI**
Yield strength(a), ksi	035	035

	040	040
	045	045
	050	050
		055
	060	060
		065
	070	070
	080	080
		100
		120
		140
		160
		190
Chemistry(b)	A	S
	B	S
	C	S
	S	S
	W	W
	X	X
	Y	X
	Z	X

		D
Carbon level[c]	H	. . .
	L	. . .
Deoxidation practice	O	O
	K	K
	F	F

(a) SAE, complete listing of applicable yield strengths shown in ksi. AISI, list of yield strengths is representative; more may be added at producer's option.

(b) A, B, C, and S under SAE represent various combinations of C, Mn, and N, and P content. These are grouped under S in AISI. X, Y, and Z in SAE represent microalloyed steels with 10 ksi, 15 ksi, and 20 ksi respective spreads between yield and tensile strength. These are grouped under X in AISI. The W grades are equivalent. There is no SAE equivalent for the AISI D chemistry.

(c) Value of carbon levels for H and L designations vary with the grade of steel in SAE.

SAE Sheet Designation System. SAE recommended practice J1392 covers high-strength hot-rolled, cold-rolled, and coated sheet steels and has replaced J410c for these particular product forms. The mechanical properties for the various grades covered by practice J1392 are given in Tables 22 and 23.

Table 22 Mechanical properties of hot-rolled high-strength sheet steel specified in SAE J1392

Grade	Yield strength (min)		Tensile strength (min)		Elongation in 2 in. (50 mm) (min)[a], %
	ksi	MPa	ksi	MPa	
035 A, B, C, S	35	240	[b]	[b]	21
035 X, Y, Z	35	240	[b]	[b]	28
A40 A, B, C, S	40	280	[b]	[b]	20
040 X, Y, Z	40	280	[b]	[b]	27
045 A, B, C, S	45	310	[b]	[b]	18
045 W	45	310	65	450	25

045 X	45	310	55	380	25
045 Y	45	310	60	410	25
045 Z	45	310	65	450	25
050 A, B, C, S	50	340	(b)	(b)	16
050 W	50	340	70	480	22
050 X	50	340	60	410	22
050 Y	50	340	65	450	22
050 Z	50	340	70	480	22
060 X	60	410	70	480	20
060 Y	60	410	75	520	20
070 X	70	480	80	550	17
070 Y	70	480	85	590	17
080 X	80	550	90	620	14
080 Y	80	550	95	650	14

(a) Elongation values are dependent upon specimen geometry (cross-sectional area). Thicker and wider specimens normally result in higher percentages.

(b) Minimum tensile strength normally does not apply.

Table 23 Mechanical properties of cold-rolled and coated high-strength sheet steel specified in SAE J1392

Grade	**Yield strength (min)**		**Tensile strength (min)**		**Elongation in 2 in. (50 mm) (min)(a), %**
	ksi	**MPa**	**ksi**	**MPa**	

035 A, B, C, S	35	240	(b)	(b)	22
035 X, Y, Z	35	240	(b)	(b)	27
040 A, B, C, S	40	280	(b)	(b)	20
040 X, Y, Z	40	280	(b)	(b)	25
045 A, B, C, S	45	310	(b)	(b)	18
045 W	45	310	65	450	22
045 X	45	310	55	380	22
045 Y	45	310	60	410	22
045 Z	45	310	65	450	22
050 A, B, C, S	50	340	(b)	(b)	16
050 X	50	340	60	410	20
050 Y	50	340	65	450	20
050 Z	50	340	70	480	20

(a) Elongation values are dependent upon specimen geometry (cross-sectional area). Thicker and wider specimens normally result in higher percentages.

(b) Minimum tensile strength normally does not apply.

A six-character code is used to describe strength level, general chemical composition, general carbon level, and the deoxidation/sulfide inclusion control system. The first, second, and third characters give the minimum yield strength in ksi; for example, 035 is 35 ksi, 040 is 40 ksi, and so forth.

The fourth character describes the general chemical composition. The letter A means carbon and manganese only; B means carbon, manganese, and nitrogen; C means carbon, manganese, and phosphorus; S means carbon and manganese with nitrogen and/or phosphorus added at producer option; W refers to weathering compositions that include silicon, phosphorus, copper, nickel, and chromium in various combinations; X refers to HSLA compositions that contain niobium, chromium, copper, molybdenum, nickel, silicon, titanium, vanadium, and zirconium added singly or in combination (along with nitrogen and/or phosphorus if desired) and that exhibit a 10 ksi (70 MPa) spread between specified minimum values of yield and tensile strengths; Y refers to the same compositions as X except with a 15 ksi (100 MPa) spread between specified minimal values of yield and tensile strengths; Z refers to the same compositions as X except with a 20 ksi (40 MPa) spread between the specified minimum values of yield and tensile strengths.

The fifth character describes the general carbon level. The letter H refers to the maximum carbon level, and L means 0.13% C maximum. The sixth character describes deoxidation/sulfide inclusion control practices. The letter K means killed and made to a fine-grain practice, F means sulfide-inclusion controlled, killed, and made to a fine-grain practice; and O refers to other than K or F.

The AISI designation system of high-strength sheet steels contains three basic components: the minimum yield strength, the chemical composition, and the deoxidation practice. A five-character code is used to describe these components.

The first three characters give the yield strength of a given grade. Yield strength is categorized in 5 ksi (35 MPa) increments from 35 to 60 ksi (241 to 414 MPa), in 10 ksi (70 MPa) increments from 60 to 80 ksi (414 to 550 MPa), in 20 ksi (140 MPa) increments from 80 to 140 ksi (550 to 965 MPa), and in 30 ksi (207 MPa) increments from 160 to 190 ksi (1100 to 1310 MPa). Thus, the designation "050" refers to a steel with a yield strength of 50 ksi (345 MPa).

The chemical composition of each grade is designated by a letter classification: S, X, W, or D. The letter S refers to structural-quality steels that contain carbon plus manganese; carbon plus manganese and phosphorus; carbon plus manganese and nitrogen; or carbon plus manganese, phosphorus, and nitrogen. Recovery-annealed steels, except those with the designation X, are included in this category. The letter X refers to low-alloy steel grades containing niobium, chromium, copper, molybdenum, nickel, silicon, titanium, vanadium, and zirconium either singly or in combination. Weathering steels containing silicon, phosphorus, copper, nickel, and chromium in various combinations are indicated by the letter W. Dual-phase steels containing martensite or other transformation products in a ferrite matrix are designated by the letter D. Dual-phase steels exhibit very high work-hardening rates, and, as a result, formed parts have significantly higher strengths than do the original flat-rolled sheets. Consequently, the yield strength of a dual-phase steel is designated as the strength after a 5% strain; for example, an 080D grade exhibits an 80 ksi (550 MPa) yield strength after 5% strain.

Deoxidation practice is also designated by a letter classification. The letter F means killed plus sulfide-inclusion controlled, K means killed, and O means nonkilled. For example, the steel designation 040SF would mean a minimum yield strength of 40 ksi (275 MPa), structural quality, killed.

UNS Designations

The Unified Numbering System (UNS) has been developed by ASTM and SAE and several other technical societies, trade associations, and United States government agencies. A UNS number, which is a designation of chemical composition and not a specification, is assigned to each chemical composition of a metallic alloy. Available UNS designations are included in the tables in this article.

The UNS designation of an alloy consists of a letter and five numerals. The letters indicate the broad class of alloys; the numerals define specific alloys within that class. Existing designation systems, such as the SAE-AISI system for steels, have been incorporated into UNS designations. For example, the UNS prefix letter for carbon and alloy steels is G, and the first four digits are the SAE-AISI designation, for example, G10400. The intermediate letters B and L of the SAE-AISI system are replaced by making the fifth digit of the UNS designation 1 and 4 respectively, while the prefix letter E for electric furnace steels is designated in UNS system by making the fifth digit 6. The SAE-AISI steels which have a hardenability requirement indicated by the suffix letter H are designated by the H*xxxxx* series in the UNS system. Carbon and alloy steels not referred to in the SAE-AISI system are categorized under the prefix letter K. The UNS designation system is described in greater detail in SAE J1086 and ASTM E 527.

AMS Designations

Aerospace Materials Specifications (AMS), published by SAE, are complete specifications that are generally adequate for procurement purposes. Most of the AMS designations pertain to materials intended for aerospace applications; the specifications can include mechanical property requirements significantly more severe than those for grades of steel having similar compositions but intended for other applications. Processing requirements, such as for consumable electrode remelting, are common in AMS steels. Chemical compositions for AMS grades of carbon and steel alloys are given in Tables 24 and 25.

Table 24 Product descriptions and carbon contents for wrought carbon steels covered by AMS designations

AMS designation	Product form	Carbon content	Nearest SAE-AISI grade	UNS No.
5010H	Bars (screw machine stock)	. . .	1112	G12120
5020C	Bars, forgings, tubing	0.32-0.39(a)	11L37	G11374
5022K	Bars, forgings, tubing	0.14-0.20	1117	G11170
5024F	Bars, forgings, tubing	0.32-0.39(b)	1137	G11370
5032D	Wire (annealed)	0.18-0.23	1020	G10200
5036G	Sheet, strip (aluminum coated, low carbon)	. . .	. . .	. . .
5040H	Sheet, strip (deep-forming grade)	0.15 max	1010	G10100
5042H	Sheet, strip (forming grade)	0.15 max	1010	G10100
5044F	Sheet, strip (half-hard temper)	0.15 max	1010	G10100
5045E	Sheet, strip (hard temper)	0.25 max	1020	G10200
5046	Sheet, strip, plate (annealed)	. . .	1020	G10200
5047C	Sheet, strip (aluminum killed, deep forming grade)	0.08-0.13	1010	G10100
5050H	Tubing (seamless, annealed)	0.15 max	1010	G10100
5053F	Tubing (welded, annealed)	0.15 max	1010	G10100
5060F	Bars, forgings, tubing	0.13-0.18	1015	G10150
5061D	Bars, wire	Low	. . .	K00802
5062E	Bars, forgings, tubing, plate, sheet, strip	Low	. . .	K02508
5069D	Bars, forgings, tubing	0.15-0.20	1018	G10180

5070F	Bars, forgings	0.18-0.23	1022	G10220
5075E	Tubing (seamless, cold drawn, stress relieved)	0.22-0.28	1025	G10250
5077D	Tubing (welded)	0.22-0.28	1025	G10250
5080G	Bars, forgings, tubing	0.31-0.38	1035	G10350
5082D	Tubing (seamless, stress relieved)	0.31-0.38	1035	G10350
5085D	Plate, sheet, strip (annealed)	0.47-0.55	1050	G10500
5110E	Wire (carbon, spring temper, cold drawn)	0.75-0.88	1080	G10800
5112H	Wire (spring quality music wire, cold drawn)	0.70-1.00	1090	G10900
5115F	Wire (valve spring quality, hardened and tempered)	0.60-0.75	1070	G10700
5120J	Strip	0.68-0.80	1074	G10740
5121F	Sheet, strip	0.90-1.04	1095	G10950
5122F	Strip (hard temper)	0.90-1.04	1095	G10950
5132G	Bars	0.90-1.30	1095	G10950

(a) Contains 1.5% Mn and 0.025% Pb.

(b) Contains 1.5% Mn

Table 25 Alloy steel product forms and compositions covered by AMS specifications

AMS designation	**Product form**(a)	**Nominal composition, %**					**Nearest proprietary or SAE-AISI grade**	**UNS No.**
		C	**Cr**	**Ni**	**Mo**	**Other**		
6250H	Bars, forgings, tubing	0.07-0.13	1.5	3.5	. . .	. . .	3310	K44910
6255	Bars, forgings, tubing (P, DVM)	0.16-0.22	1.45	. . .	1.0	1.1 Si, 0.08 Al	CBS 600	K21940

6256A	Bars, forgings, tubing (P, DVM)	0.10-0.16	1.0	3.0	4.5	0.08 Al, 0.38 V	CBS 1000M	K71350
6260K	Bars, forgings, tubing (carburizing)	0.07-0.13	1.2	3.2	0.12	. . .	9310	G93106
6263G	Bars, forgings, tubing (carburizing grade, aircraft)	0.11-0.17	1.2	3.2	0.12	. . .	9315	. . .
6264G	Bars, forgings, tubing (carburizing)	0.14-0.20	1.2	3.2	0.12	. . .	9317	K44414
6265F	Bars, forgings, tubing (P, CVM)	0.07-0.13	1.2	3.25	0.12	. . .	9310	G93106
6266F	Bars, forgings, tubing	0.08-0.13	0.50	1.82	0.25	0.003 B, 0.06 V	43BV12	K21028
6267C	Bars, forgings, tubing	0.07-0.13	1.2	3.25	0.12	. . .	9310	G93106
6270L	Bars, forgings, tubing	0.11-0.17	0.50	0.55	0.20	. . .	8615	G86150
6272G	Bars, forgings, tubing	0.15-0.20	0.50	0.55	0.20	. . .	8617	G86170
6274K	Bars, forgings, tubing	0.18-0.23	0.50	0.55	0.20	. . .	8620	G86200
6275E	Bars, forgings, tubing	0.15-0.20	0.40	0.45	0.12	0.002 B	94B17	G94171
6276F	Bars, forgings, tubing (CVM)	0.18-0.23	0.50	0.55	0.2	. . .	8620	G86200
6277D	Bars, forgings, tubing (VAR, ESR)	0.18-0.23	0.50	0.55	0.20	. . .	8620	G86200
6278	Bars, forgings, tubing (for bearing applications; P, DVM)	0.11-0.15	4.1	3.4	4.2	12. V	. . .	. . .
6280G	Bars, forgings, rings	0.28-0.33	0.50	0.55	0.20	. . .	8630	G86300
6281F	Tubing (mechanical)	0.28-0.33	0.5	0.55	0.20	. . .	8630	G86300

6282F	Tubing (mechanical)	0.33-0.38	0.50	0.55	0.25	. . .	8735	G87350
6290F	Bars, forgings (carburizing)	0.11-0.17	. . .	1.8	0.25	. . .	4615	G46150
6292F	Bars, forgings (carburizing)	0.15-0.20	. . .	1.8	0.25	. . .	4617	G46170
6294F	Bars, forgings	0.17-0.22	. . .	1.8	0.25	. . .	4620	G42600
6299C	Bars, forgings, tubing	0.17-0.23	0.50	1.8	0.25	. . .	4320H	H43200
6300C	Bars, forgings	0.35-0.40	. . .	. . .	0.25	. . .	4037	G40370
6302E	Bars, forgings, tubing (low alloy, heat resistant)	0.28-0.33	1.25	. . .	0.50	0.65 Si, 0.25 V	17-22A(S)	K23015
6303D	Bars, forgings	0.25-0.30	1.25	. . .	0.50	0.65 Si, 0.85 V	17-22A(V)	K22770
6304G	Bars, forgings, tubing (low alloy, heat resistant)	0.40-0.50	0.95	. . .	0.55	0.30 V	17-22A	K14675
MAM 6304(b)	Bars, forgings, tubing (low alloy, heat resistant)	0.40-0.50	0.95	. . .	0.55	0.30 V	17-22A	K14675
6305A	Bars, forgings, tubing (VAR)	0.40-0.50	0.95	. . .	0.55	0.30 V	17-22A	K14675
6308A	Bars, forgings (VAR, ESR)	0.07-0.13	1.0	2.0	3.2	2.0 Cu, 0.10 V, 0.90 Si	Pyrowear alloy 53	K71040
6312E	Bars, forgings, tubing	0.38-0.43	. . .	1.8	0.25	. . .	4640	K22440
6317E	Bars, forgings (heat treated; 860 MPa tensile strength)	0.38-0.43	. . .	1.8	0.25	. . .	4640	K22440
6320H	Bars, forgings, rings	0.33-0.38	0.50	0.55	0.25	. . .	8735	G87350
6321D	Bars, forgings, tubing	0.38-0.43	0.42	0.30	0.12	0.003 B	81B40	K03810

6322K	Bars, forgings, rings	0.38-0.43	0.50	0.55	0.25	. . .	8740	G87400
6323G	Tubing (mechanical)	0.38-0.43	0.50	0.55	0.25	. . .	8740	G87400
6324E	Bars, forgings, tubing	0.38-0.43	0.65	0.70	0.25	. . .	8740 mod	K11640
6325F	Bars, forgings (heat treated; 725 MPa tensile strength)	0.38-0.43	0.50	0.55	0.25	. . .	8740	G87400
6327G	Bars, forgings (heat treated; 860 MPa tensile strength)	0.38-0.43	0.50	0.55	0.25	. . .	8740	G87400
6328H	Bars, forgings, tubing	0.48-0.53	0.50	0.55	0.25	. . .	8750	K13550
6330D	Bars, forgings, tubing	0.33-0.38	0.65	1.25	. . .	. . .	3135	K22033
6342G	Bars, forgings, tubing	0.38-0.43	0.80	1.0	0.25	. . .	9840	G98400
6348A	Bars (normalized)	0.28-0.33	0.95	. . .	0.20	. . .	4130	G41300
6349A	Bars (normalized)	0.38-0.43	0.95	. . .	0.20	. . .	4140	G41400
6350G	Plate, sheet, strip	0.28-0.33	0.95	. . .	0.20	. . .	4130	G41300
6351D	Plate, sheet, strip (spheroidized)	0.28-0.33	0.95	. . .	0.20	. . .	4130	G41300
6352E	Plate, sheet, strip	0.33-0.38	0.95	. . .	0.2	. . .	4135	G41350
6354C	Plate, sheet, strip	0.10-0.17	0.62	. . .	0.2	0.75 Si, 0.10 Zr	NAX 9115-AC	K11914
6355K	Plate, sheet, strip	0.28-0.33	0.50	0.55	0.20	. . .	8630	G86300
6356C	Plate, sheet, strip	0.30-0.35	0.95	. . .	0.20	. . .	4132	K13247

6357F	Plate, sheet, strip	0.33-0.38	0.50	0.5	0.25	. . .	8735	G87350
6358F	Plate, sheet, strip	0.38-0.43	0.50	0.55	0.25	. . .	8740	G87400
6359E	Plate, sheet, strip	0.38-0.43	0.80	1.8	0.25	. . .	4340	G43400
6360H	Tubing (seamless, normalized or stress relieved)	0.28-0.33	0.95	. . .	0.20	. . .	4130	G41300
6361B	Tubing (seamless, round; 860 MPa tensile strength)	0.28-0.33	0.95	. . .	0.2	. . .	4130	G41300
6362C	Tubing (seamless; 1035 MPa tensile strength)	0.28-0.33	0.95	. . .	0.2	. . .	4130	G41300
6365G	Tubing (seamless, normalized or stress relieved)	0.33-0.38	0.95	. . .	0.20	. . .	4135	G41350
6370J	Bars, forgings, rings	0.28-0.33	0.95	. . .	0.2	. . .	4130	G41300
6371G	Tubing (mechanical)	0.28-0.33	0.95	. . .	0.20	. . .	4130	G41300
6372G	Tubing (mechanical)	0.33-0.38	0.95	. . .	0.20	. . .	4135	G41350
6373C	Tubing (welded)	0.28-0.33	0.95	. . .	0.20	. . .	4130	G41300
6378C	Bars (die drawn, free machining; 895 MPa yield strength)	0.39-0.48	0.95	. . .	0.20	0.015 Te	4142H	K11542
6379A	Bars (die drawn and tempered; 1140 MPa yield strength)	0.40-0.53	0.95	. . .	0.20	0.05 Te	4140 mod	G41400
6381D	Tubing	0.38-0.43	0.95	. . .	0.20	. . .	4140	G41400
6382J	Bars, forgings	0.38-0.43	0.95	. . .	0.20	. . .	4140	G41400
6385D	Plate, sheet, strip	0.27-	1.25	. . .	0.50	0.65 Si, 0.25 V	17-22A(S)	K23015

		0.33						
6386B(1)	Plate, sheet (heat treated; 620 and 690 MPa yield strength)	0.15-0.21	0.50-0.80	. . .	0.18-0.28	0.40-0.80 Si, 0.05-0.15 Zr	. . .	K11856
6386B(2)	Plate, sheet (heat treated; 620 and 690 MPa yield strength)	0.12-0.21	0.40-0.65	. . .	0.15-0.25	0.20-0.35 Si, 0.01-0.03 Ti, 0.03-0.08 V, 0.0005-0.005 B	. . .	K11630
6386B(3)	Plate, sheet (heat treated; 620 and 690 MPa yield strength)	0.10-0.20	. . .	. . .	1.10-1.50	0.15-0.30 Si, 0.001-0.005 B	. . .	K11511
6386(4)	Plate, sheet (heat treated; 620 and 690 MPa yield strength)	0.13-0.20	0.85-1.20	. . .	0.15-0.25	0.20-0.40 Cu, 0.20-0.35 Si, 0.04-0.10 Ti, 0.0015-0.005 B	. . .	K11662
6386B(5)	Plate, sheet (heat treated; 620 and 690 MPa yield strength)	0.12-0.21	. . .	. . .	0.45-0.70	0.20-0.35 Si, 0.001-0.005 B	. . .	K11625
6390B	Tubing (mechanical, special surface quality)	0.38-0.43	0.95	. . .	0.20	. . .	4140	G41400
6395C	Plate, sheet, strip	0.38-0.43	0.95	. . .	0.20	. . .	4140	G41400
6396B	Sheet, strip, plate (annealed)	0.49-0.55	0.80	1.8	0.25	. . .	. . .	K22950
6406C	Plate, sheet, strip (annealed)	0.41-0.46	2.1	. . .	0.58	1.6 Si, 0.05 V	X200	K34378
6407D	Bars, forgings, tubing	0.27-0.33	1.2	2.05	0.45	. . .	HS-220	K33020
6408	Bars, forgings, tubing (annealed, ESR, CVM, VAR, P)	0.35-0.45	5.2	. . .	1.5	1.0 V	. . .	T20813
6409	Bars, forgings, tubing (normalized and tempered, quality cleanliness)	0.38-0.43	0.80	1.8	0.25	. . .	4340	G43400
6411C	Bars, forgings, tubing (CM)	0.28-0.33	0.85	1.8	0.40	. . .	4330 mod	K23080
6412H	Bars, forgings	0.35-0.40	0.80	1.8	0.25	. . .	4337	G43370

6413G	Tubing (mechanical)	0.35-0.40	0.80	1.8	0.25	. . .	4337	G43370
6414E	Bars, forgings, tubing (CVM)	0.38-0.43	0.80	1.8	0.25	. . .	4340	G43400
6415L	Bars, forgings, tubing	0.38-0.43	0.80	1.8	0.25	. . .	4340	G43400
MAM 6415(b)	Bars, forgings, tubing	0.38-0.43	0.80	1.8	0.25	. . .	4340	G43400
6416B	Superseded by AMS 6419							
6417C	Bars, forgings, tubing (CM)	0.38-0.43	0.82	1.8	0.40	1.6 Si, 0.08 V	300M	K44220
6418F	Bars, forgings, tubing, rings	0.23-0.28	0.30	1.8	0.40	1.3 Mn, 1.5 Si	Hy-tuf	K32550
6419C	Bars, forgings, tubing (CVM)	0.40-0.45	0.82	1.8	0.40	1.6 Si, 0.08 V	300M	K44220
6421B	Bars, forgings, tubing	0.35-0.40	0.80	0.85	0.20	0.003 B	98B37 mod	. . .
6422E	Bars, forgings, tubing	0.38-0.43	0.80	0.85	0.20	0.003 B	98BV40 mod	K11940
6423C	Bars, forgings, tubing	0.40-0.46	0.92	0.75	0.52	0.003 B	. . .	K24336
6424B	Bars, forgings, tubing	0.49-0.59	0.80	1.8	0.25	. . .	. . .	K22950
6426C	Bars, forgings, tubing (CVM)	0.80-0.90	1.0	. . .	0.58	0.75 Si	52CB	K18597
6427G	Bars, forgings, tubing	0.28-0.33	0.85	1.8	0.42	0.08 V	4330 mod	K23080
6428D	Bars, forgings, tubing	0.32-0.38	0.80	1.8	0.35	0.20 V	4335 mod	K23477
6429C	Bars, forgings, tubing, rings (CVM)	0.33-0.38	0.78	1.8	0.35	0.20 V	4335 mod	K33517

6430C	Bars, forgings, tubing, rings (special grade)	0.32-0.38	0.78	1.8	0.35	0.20 V	4335 mod	K33517
6431G	Bars, forgings, tubing (CVM)	0.45-0.50	1.05	0.55	1.0	0.11 V	D-6ac	K24728
6432A	Bars, forgings, tubing	0.43-0.49	1.05	0.55	1.0	0.12 V	D-6a	K24728
6433C	Plate, sheet, strip (special grade)	0.33-0.38	0.80	1.8	0.35	0.20 V	4335 mod	K33517
6434C	Plate, sheet, strip	0.33-0.38	0.78	1.8	0.35	0.20 V	4335 mod	K33517
6435C	Plate, sheet, strip (P, CM, annealed)	0.33-0.38	0.78	1.8	0.35	0.20 V	4335 mod	K33517
6436B	Plate, sheet, strip (low alloy, heat resistant, annealed)	0.25-0.30	1.25	. . .	0.50	0.65 Si, 0.85 V	17-22A(V)	K22770
6437D	Plate, sheet, strip	0.38-0.43	5.0	. . .	1.3	0.5 V	H-11	T20811
6438C	Plate, sheet, strip (P, CM)	0.45-0.50	1.05	0.55	1.0	0.11 V	D-6ac	K24728
6439B	Plate, sheet, strip (annealed, CVM)	0.42-0.48	1.05	0.55	1.0	0.12 V	D-6ac	K24729
6440J	Bars, forgings, tubing (for bearing applications)	0.98-1.10	1.45	. . .	. . .	. . .	52100	G52986
6441G	Superseded by AMS 6440							
6442E	Bars, forgings (for bearing applications)	0.98-1.10	0.50	. . .	. . .	. . .	50100	G50986
6443E	Bars, forgings, tubing (CVM)	0.98-1.10	1.0	. . .	. . .	. . .	51100	G51986
6444G	Bars, wire, forgings, tubing (P, CVM)	0.98-1.10	1.45	. . .	. . .	. . .	52100	G52986
6445E	Bars, wire, forgings, tubing (CVM)	0.92-1.02	1.05	. . .	. . .	1.1 Mn	51100 mod	K22097

6446C	Bars, forgings (ESR)	0.98-1.10	1.00	. . .	. . .	. . .	51100	G51986
6447C	Bars, forgings, tubing (ESR)	0.98-1.10	1.45	. . .	. . .	. . .	52100	G52986
6448F	Bars, forgings, tubing	0.48-0.53	0.95	. . .	. . .	0.22 V	6150	G61500
6449C	Bars, forgings, tubing (for bearing applications)	0.98-1.10	1.0	. . .	. . .	. . .	51100	G51986
6450E	Wire (spring)	0.48-0.53	0.95	. . .	. . .	0.22 V	6150	G61500
6451A	Wire, spring (oil tempered)	0.51-0.59	0.65	. . .	. . .	1.4 Si	9254	G92540
6454	Sheet, strip, plate (P, CM)	0.38-0.43	0.80	1.8	0.25	. . .	4340	G43400
6455F	Plate, sheet, strip	0.48-0.53	0.95	. . .	. . .	0.22 V	6150	G61500
6470H	Bars, forgings, tubing (nitriding)	0.38-0.43	1.6	. . .	0.35	1.1 Al	135 mod	K24065
6471C	Bars, forgings, tubing (nitriding, CVM)	0.38-0.43	1.6	. . .	0.35	1.2 Al	135 mod	K24065
6472B	Bars, forgings (nitriding, heat treated; 770 MPa tensile strength)	0.38-0.43	1.6	. . .	0.35	1.1 Al	135 mod	K24065
6475E	Bars, forgings, tubing (nitriding)	0.21-0.26	1.1	3.5	0.25	1.25 Al	. . .	K52355
6485	Bars, forgings	0.38-0.43	5.0	. . .	1.3	0.50 V	H-11	T20811
6487	Bars, forgings (P, CVM)	0.38-0.43	5.0	. . .	1.3	0.50 V	H-11	T20811
6488D	Bars, forgings (P)	0.38-0.43	5.0	. . .	1.3	0.50 V	H-11	T20811
6490D	Bars, forgings, tubing (for	0.77-	4.0	. . .	4.2	1.0 V	M-50	T11350

	bearing applications: P, CVM)	0.85						
6491A	Bars, forgings, tubing (for bearing applications; P, DVM)	0.80-0.85	4.1	. . .	4.2	1.0 V	M-50	T11350
6512B	Bars, forgings, tubing, rings (annealed)	. . .	. . .	18	4.9	7.8 Co, 0.40 Ti, 0.10 Al	Maraging 250	K92890
6514B	Bars, forgings, tubing, rings (annealed, CM)	. . .	. . .	18.5	4.9	9.0 Co, 0.65 Ti, 0.10 Al	Maraging 300	K93120
6518A	Sheet, strip, plate (solution treated, DVM)	. . .	. . .	19.0	3.0	0.10 Al, 1.4 Ti	. . .	. . .
6519A	Bars, forgings, tubing, springs (annealed, DVM)	. . .	. . .	19.0	3.0	0.10 Al, 1.4 Ti	. . .	. . .
6520B	Plate, sheet, strip (solution heat treated, CM)	. . .	. . .	18	4.9	7.8 Co, 0.40 Ti, 0.10 Al	Maraging 250	K92890
6521A	Plate, sheet, strip (solution heat treated, CM)	. . .	. . .	18.5	4.9	9.0 Co, 0.65 Ti, 0.10 Al	Maraging 300	K93120
6522	Plate (P, VM)	. . .	2.0	10.0	1.0	14.0 Co	AF 1410	K92571
6523C	Sheet, strip, plate (annealed, CVM)	0.17-0.23	0.75	9.0	1.0	0.09 V, 4.5 Co	HP 9-4-20	K91472
6524B	Sheet, strip, plate (annealed, CVM)	0.29-0.34	1.0	7.5	1.0	0.09 V, 4.5 Co	HP 9-4-30	K91283
6525A	Bars, forgings, tubing, rings (CVM)	0.17-0.23	0.75	9.0	1.0	0.09 V, 4.5 Co	HP 9-4-20	K91283
6526C	Bars, forgings, tubing, rings (annealed, CVM)	0.29-0.34	1.0	7.5	1.0	4.5 Co, 0.09 V	HP 9-4-30	K91313
6527	Bars, forgings (P, VM)	0.13-0.17	2.0	10.0	1.0	14 Co	AF 1410	K92571
6528	Bars (normalized, special aircraft quality cleanliness)	0.28-0.33	0.95	. . .	0.20	. . .	4130	G41300
6529	Bars (normalized, special aircraft quality cleanliness)	0.38-0.43	0.95	. . .	0.20	. . .	4140	G41400
6530H	Tubing (seamless)	0.28-	0.55	0.50	0.20	. . .	8630	G86300

		0.33						
6535G	Tubing (seamless)	0.28-0.33	0.50	0.55	0.20	. . .	8630	G86300
6543A	Bars, forgings (solution treated, DVM)	0.10-0.14	2.0	10.0	1.0	8.0 Co	. . .	K91970
6544A	Plate (solution treated, VM)	0.10-0.14	2.0	10.0	1.0	8.0 Co	. . .	K92571
6546C	Plate, sheet, strip (annealed, P, CM)	0.24-0.30	0.48	8.0	0.48	4.0 Co, 0.09 V	HP 9-4-25	K91122
6550H	Tubing (welded)	0.28-0.33	0.55	0.50	0.20	. . .	8630	G86300

(a) P, premium quality; CVM, consumable vacuum melted; CVAR, consumable vacuum arc remelted; ESR, electroslag remelted; DVM, double vacuum melted; VAR, vacuum arc remelted; CM, consumable electrode remelted; VM, vacuum melted.

(b) MAM, metric aerospace material specifications

ASTM (ASME) Designations

As noted previously, the most widely used standard specifications for steel products are those published by ASTM. These are complete specifications, generally adequate for procurement purposes. Many ASTM specifications apply to specific products, such as A 574, for alloy steel socket head cap screws. These specifications are generally oriented toward performance of the fabricated end product, with considerable latitude in chemical composition of the steel used to make the end product.

ASTM specifications represent a consensus among producers, specifiers, fabricators, and users of steel mill products. In many cases, the dimensions, tolerances, limits, and restrictions in the ASTM specifications are the same as the corresponding items of the standard practices in the AISI *Steel Products Manuals.* Many of the ASTM specifications have been adopted by the American Society of Mechanical Engineers (ASME) with little or no modification; ASME uses the prefix "S" and the ASTM designation for these specifications. For example, ASME SA-213 and ASTM A 213 are identical.

Steel products can be identified by the number of the ASTM specification to which they are made. The number consists of the letter "A" (for ferrous materials) and an arbitrary, serially assigned number. Citing the specification number, however, is not always adequate to completely describe a steel product. For example, A 434 is the specification for heat treated (hardened and tempered) alloy steel bars. To completely describe steel bars indicated by this specification the grade (SAE-AISI designation in this case) and class (required strength level) must also be indicated. A 434 also incorporates, by reference, two standards for test methods and A 29, the general requirements for bar products.

SAE-AISI designations for the compositions of carbon and alloy steels are normally incorporated into the ASTM specifications for bars, wires, and billets for forging. Some ASTM specifications for sheet products include SAE-AISI designations for composition. ASTM specifications for plates and structural shapes generally specify the limits and ranges of chemical composition directly, without the SAE-AISI designations. Table 26 includes a list of some of the ASTM specifications that incorporate SAE-AISI designations for compositions of the different grades of steel.

Table 26 ASTM specifications that incorporate SAE-AISI designations

ASTM specifications	**Subject**
A 29	Carbon and alloy steel bars, hot rolled and cold finished
A 108	Standard quality cold-finished carbon steel bars
A 295	High carbon-chromium ball and roller bearing steel
A 304	Alloy steel bars having hardenability requirements
A 322	Hot-rolled alloy steel bars
A 331	Cold-finished alloy steel bars
A 434	Hot-rolled or cold-finished quenched and tempered alloy steel bars
A 505	Hot-rolled and cold-rolled alloy steel sheet and strip
A 506	Regular quality hot-rolled and cold-rolled alloy steel sheet and strip
A 507	Drawing quality hot-rolled and cold-rolled alloy steel sheet and strip
A 510	Carbon steel wire rods and coarse round wire
A 534	Carburizing steels for antifriction bearings
A 535	Special quality ball and roller bearing steel
A 544	Scrapless nut quality carbon steel wire
A 545	Cold-heading quality carbon steel wire for machine screws
A 546	Cold-heading quality medium-high-carbon steel wire for hexagon-head bolts
A 547	Cold-heading quality alloy steel wire for hexagon-head bolts
A 548	Cold-heading quality carbon steel wire for tapping or sheet metal screws
A 549	Cold-heading quality carbon steel wire for wood screws

A 575	Merchant quality hot-rolled carbon steel bars
A 576	Special quality hot-rolled carbon steel bars
A 646	Premium quality alloy steel blooms and billets for aircraft and aerospace forgings
A 659	Commercial quality hot-rolled carbon steel sheet and strip
A 682	Cold-rolled spring quality carbon steel strip, generic
A 684	Untempered cold-rolled high-carbon steel strip
A 689	Carbon and alloy steel bars for springs
A 711	Carbon and alloy steel blooms, billets, and slabs for forging
A 713	High-carbon spring steel wire for heat-treated components
A 752	Alloy steel wire rods and coarse round wire
A 827	Carbon steel plates for forging and similar applications
A 829	Structural quality alloy steel plates
A 830	Structural quality carbon steel plates

Generic Specifications. Several ASTM specifications, such as A 29, contain the general requirements common to each member of a broad family of steel products. Table 27 lists several of these generic specifications, which generally must be supplemented by another specification describing a specific mill form or intermediate fabricated product.

Table 27 Generic ASTM specifications

ASTM specification(a)	**Title**
A 6/A 6M	General requirements for rolled steel plates, shapes, sheet piling, and bars for structural purposes
A 20/A 20M	General requirements for steel plates for pressure vessels
A 29/A 29M	General requirements for hot-rolled and cold-finished carbon and alloy steel bars
A 450/A 450M	General requirements for carbon, ferritic-alloy, and austenitic alloy tubes

A 505	General requirements for hot-rolled and cold-rolled alloy steel sheet and strip
A 530/A 530M	General requirements for specialized carbon and alloy steel pipe
A 682	General requirements for cold-rolled spring quality high-carbon steel strip

(a) The suffix "M" indicates that a metric version of the specification is available

Sheet Products. Limits and ranges of chemical compositions for carbon steel sheet products with ASTM specifications that do not incorporate SAE-AISI designations are listed in Table 28. ASTM specifications for sheet products that do include SAE-AISI designations are listed in Table 26.

Table 28 Composition ranges and limits for plain carbon sheet and strip (ASTM specifications)

ASTM specification	Description[(a)]	Composition[(b)], %				
		C	Mn	P	S	Other
A 611	CR SQ grades A, B, C, E	0.20	0.60	0.04	0.04	(c)
	Grade D (type 1)	0.20	0.90	0.04	0.04	(c)
	Grade D (type 2)	0.15	0.60	0.20	0.04	(c)
A 366	CR CQ	0.15	0.60	0.35	0.04	(c)
A 109	CR strip tempers 1, 2, 3	0.25	0.60	0.035	0.04	(c)
	Tempers 4, 5	0.15	0.60	0.035	0.04	(c)
A 619	CR DQ	0.10	0.50	0.025	0.035	. . .
A 620	CR DQSK	0.10	0.50	0.025	0.035	(d)
A 570	HR SQ grades 30, 33, 36, and 40	0.25	0.90	0.04	0.05	(c)
	Grades 45, 50, and 55	0.25	1.35	0.04	0.05	(c)
A 569	HR CQ	0.15	0.60	0.035	0.040	(c)
A 621	HR DQ	0.10	0.50	0.025	0.035	. . .

A 622	HR DQSK	0.10	0.50	0.025	0.035	(d)
A 414	Pressure vessel grade A	0.15	0.90	0.035	0.040	(c)
	Grade B	0.22	0.90	0.035	0.040	(c)
	Grade C	0.25	0.90	0.035	0.040	(c)
	Grade D	0.25	1.20	0.035	0.040	(c)(e)
	Grade E	0.27	1.20	0.035	0.040	(c)(e)
	Grade F	0.31	1.20	0.035	0.040	(c)(e)
	Grade G	0.31	1.35	0.035	0.040	(c)(e)

(a) CR, cold-rolled; HR, hot rolled; SQ, structural quality; DG, drawing quality; DQSK, drawing quality, special killed; CQ, commercial quality.

(b) All values are maximum.

(c) Copper when specified as copper-bearing steel: 0.20% min.

(d) Aluminum as deoxidizer usually exceeds 0.010% in the product.

(e) Killed steel can be supplied upon request to the manufacturer for grades D through G. When silicon-killed steel is specified, a range of 0.15-0.30% Si shall be supplied.

Plate and Structural Shapes. ASTM specifications for plate and structural shapes generally do not incorporate SAE-AISI designations. Limits and ranges of chemical composition in ASTM specifications for carbon and alloy structural plate are listed in Table 29.

Table 29 ASTM specifications of chemical composition for structural plate made of alloy steel or carbon steel

ASTM specification	Material grade or type	Composition$^{(a)}$, %									
		C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Others
Alloy steel											
A 514	A	0.15-0.21	0.80-1.10	0.035	0.04	0.40-0.80	0.50-0.80	. . .	0.18-0.28	. . .	Zr, 0.05-0.15; B, 0.0025
	B	0.12-0.21	0.70-1.00	0.035	0.04	0.20-0.35	0.40-0.65	. . .	0.15-0.25	. . .	V, 0.03-0.08; Ti, 0.01-0.03; B, 0.0005-0.005
	C	0.10-0.20	1.10-1.50	0.035	0.04	0.15-0.30	. . .	. . .	0.15-0.30	. . .	B, 0.001-0.005
	E	0.12-0.20	0.40-0.70	0.035	0.04	0.20-0.40	1.40-2.00	. . .	0.40-0.60	. . .	Ti, 0.01-0.10$^{(b)}$; B, 0.001-0.005
	F	0.10-0.20	0.60-1.00	0.035	0.04	0.15-0.35	0.40-0.65	0.70-1.00	0.40-0.60	0.15-0.50	V, 0.03-0.08; B, 0.0005-0.006
	H	0.12-0.21	0.95-1.30	0.035	0.04	0.20-0.35	0.40-0.65	0.30-0.70	0.20-0.30	. . .	V, 0.03-0.08; B, 0.0005-0.005
	J	0.12-0.21	0.45-0.70	0.035	0.04	0.20-0.35	. . .	. . .	0.50-0.65	. . .	B, 0.001-0.005
	M	0.12-0.21	0.45-0.70	0.035	0.04	0.20-0.35	. . .	1.20-1.50	0.45-0.60	. . .	B, 0.001-0.005
	P	0.12-0.21	0.45-0.70	0.035	0.04	0.20-0.35	0.85-1.20	1.20-1.50	0.45-0.60	. . .	B, 0.001-0.005
	Q	0.14-0.21	0.95-1.30	0.035	0.04	0.15-0.35	1.00-1.50	1.20-1.50	0.40-0.6	. . .	V, 0.03-0.08
	R	0.15-0.80	0.85-1.15	0.035	0.04	0.20-0.35	0.35-0.65	0.90-1.10	0.15-0.25	. . .	V, 0.03-0.08
	S	0.10-0.20	1.10-1.50	0.035	0.04	0.15-0.35	. . .	. . .	0.10-0.35	. . .	B, 0.001-0.005; Nb, 0.06 max$^{(c)}$
	T	0.08-0.14	1.20-1.50	0.035	0.010	0.40-0.60	. . .	. . .	0.45-0.60	. . .	V, 0.03-0.08; B, 0.001-0.005

A 709	100, 100W	(equivalent to A 514-A, B, C, E, F, H, J, M, P, Q)									
A 710	A	0.07	0.40-0.70	0.025	0.025	0.40	0.60-0.90	0.70-1.00	0.15-0.25	1.00-1.30	Nb, 0.02 min
	B	0.06	0.40-0.65	0.025	0.025	0.15-0.40	. . .	1.20-1.50	. . .	1.00-1.30	Nb, 0.02 min
	C	0.07	1.30-1.65	0.25	0.25	0.04	. . .	0.70-1.00	0.15-0.25	1.00-1.30	Nb, 0.02 min
Carbon steel											
A 36	. . .	0.29(d)	0.80-1.20(d)	0.04	0.05	0.15-0.40(d)	. . .	. . .	. . .	0.20(e)	. . .
A 131	A	0.26(d)	(f)	0.05	0.05	. . .	. . .	. . .	. . .	. . .	. . .
	B	0.21	0.80-1.10(g)	0.04	0.04	0.3	. . .	. . .	. . .	. . .	. . .
	D	0.21	0.70-1.35(d)(g)	0.04	0.04	0.10-0.35	. . .	. . .	. . .	. . .	. . .
	E	0.18	0.70-1.35(g)	0.04	0.04	0.10-0.35	. . .	. . .	. . .	. . .	. . .
	CS, DS	0.16	1.00-1.35(g)	0.04	0.04	0.10-0.35	. . .	. . .	. . .	. . .	. . .
A 283	A	0.14	0.90	0.04	0.05	0.04(d)	. . .	. . .	. . .	0.20(e)	. . .
	B	0.17	0.90	0.04	0.05	0.04(d)	. . .	. . .	. . .	0.20(e)	. . .
	C	0.24	0.90	0.04	0.05	0.04(d)	. . .	. . .	. . .	0.20(e)	. . .
	D	0.27	0.90	0.04	0.05	0.04(d)	. . .	. . .	. . .	0.20(e)	. . .
A 284	C	0.36(d)	0.90	0.04	0.05	0.15-0.40	. . .	. . .	. . .	. . .	. . .
	D	0.35(d)	0.90	0.04	0.05	0.15-0.40	. . .	. . .	. . .	. . .	. . .

A 529	. . .	0.27	1.20	0.04	0.05	. . .	. . .	. . .	. . .	0.20(e)	. . .
A 573	58	0.23	0.60-0.90(g)	0.04	0.05	0.10-0.35	. . .	. . .	. . .	. . .	. . .
	65	0.26(d)	0.85-1.20	0.04	0.05	0.15-0.40	. . .	. . .	. . .	. . .	. . .
	70	0.28(d)	0.85-1.20	0.04	0.05	0.15-0.40	. . .	. . .	. . .	. . .	. . .
A 678	A	0.16	0.90-1.50	0.04	0.05	0.15-0.50	0.25	0.25	0.08	0.20(e)-0.35	. . .
	B	0.20	0.70-1.60(d)	0.04	0.05	0.15-0.50	0.25	0.25	0.08	0.20(e)-0.35	. . .
	C	0.22	1.00-1.60	0.04	0.05	0.20-0.50	0.25	0.25	0.08	0.20(e)-0.35	. . .
A 709	36	0.27(d)	0.80-1.20(d)	0.04	0.05	0.15-0.40(d)	. . .	. . .	. . .	. . .	. . .

(a) When a single value is shown, it is a maximum limit, except for copper, for which a single value denotes a minimum limit.

(b) Vanadium can be substituted for part or all of the titanium on a one-for-one basis.

(c) Titanium may be present in levels up to 0.06% to protect the boron additions.

(d) Limiting values vary with plate thickness.

(e) Minimum value applicable only if copper-bearing steel is specified.

(f) Plates over 13 mm ($\frac{1}{2}$ in.) in thickness shall have a minimum manganese content not less than 2.5 times carbon content.

(g) The upper limit of manganese may be exceeded provided C + 1/6 Mn does not exceed 0.40% based on heat analysis.

Pressure-Vessel Plate. Steel plate intended for fabrication into pressure vessels must conform to different specifications than similar plate intended for structural applications. The major differences between the two groups of specifications are that pressure-vessel plate must meet requirements for notch toughness and has more stringent limits for allowable surface and edge imperfections. Limits and ranges of chemical composition for carbon and alloy steel plate for pressure vessels are given in Table 30.

Table 30 ASTM specifications of chemical compositions for pressure vessel plate made of carbon and alloy steel

ASTM specification	Material grade or type	Composition(a), %									
		C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Others
Carbon steel											
A 285	A	0.17	0.90	0.035	0.04	. . .	. . .	. . .	. . .	. . .	. . .
	B	0.22	0.90	0.035	0.04	. . .	. . .	. . .	. . .	. . .	. . .
	C	0.28	0.90	0.035	0.04	. . .	. . .	. . .	. . .	. . .	. . .
A 299	. . .	0.30(b)	0.90-1.50(b)	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
A 442	55	0.24(b)	0.80-1.10(b)	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
	60	0.27(b)	0.80-1.10(b)	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
A 455	. . .	0.33	0.85-1.20	0.035	0.04	0.10	. . .	. . .	. . .	. . .	. . .
A 515	55	0.28(b)	0.90	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
	60	0.31(b)	0.90	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
	65	0.33(b)	0.90	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
	70	0.35(b)	1.20	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
A 516	55	0.26(b)	0.60-1.20(b)	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
	60	0.27(b)	0.60-1.20(b)	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
	65	0.29(b)	0.85-	0.035	0.04	0.15-	. . .	. . .	. . .	. . .	. . .

			1.20			0.40					
	70	0.31(b)	0.85-1.20	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
A 537	Class 1, 2	0.24	0.70-1.60(b)	0.035	0.04	0.15-0.50	0.25	0.25	0.08	0.35	. . .
A 562	. . .	0.12	1.20	0.035	0.04	0.15-0.50	. . .	. . .	. . .	0.15 min	Ti min,4 × C
A 612	. . .	0.29(b)	1.00-1.50(b)	0.035	0.04	0.15-0.50(b)	0.25	0.25	0.08	0.35	V, 0.08
A 662	A	0.14	0.90-1.35	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
	B	0.19	0.85-1.50	0.035	0.04	0.15-0.40	. . .	. . .	. . .	. . .	. . .
	C	0.20	1.00-1.60	0.035	0.04	0.15-0.50	. . .	. . .	. . .	. . .	. . .
A 724	A	0.18	1.00-1.60	0.035	0.04	0.55	0.25	0.25	0.08	0.35	V, 0.08
	B	0.20	1.00-1.60	0.035	0.04	0.50	0.25	0.25	0.08	0.35	V, 0.08
	C	0.22	1.10-1.60	0.035	0.04	0.20-0.60	0.25	0.25	0.08	0.35	B, 0.005; V, 0.008
A 738	A	0.24	1.60(b)	0.035	0.04	0.15-0.50	0.25	0.50	0.08	0.35	. . .
	B	0.20	0.90-1.50	0.030	0.025	0.15-0.55	0.25	0.25	0.08	0.35	V, 0.08
	C	0.20	1.60(b)	0.030	0.025	0.15-0.55	0.25	0.25	0.08	0.35	V, 0.08
Alloy steel											
A 202	A	0.17	1.05-1.40	0.035	0.040	0.60-0.90	0.35-0.60	. . .	. . .	. . .	. . .
	B	0.25	1.05-	0.035	0.040	0.60-	0.35-	. . .	. . .	. . .	. . .

			1.40			0.90	0.60				
A 203	A	0.23(b)	0.80(b)	0.035	0.040	0.15-0.40	. . .	2.10-2.50	. . .	. . .	. . .
	B	0.25(b)	0.80(b)	0.035	0.040	0.15-0.40	. . .	2.10-2.50	. . .	. . .	. . .
	D	0.20(b)	0.80(b)	0.035	0.040	0.15-0.40	. . .	3.25-3.75	. . .	. . .	. . .
	E,F	0.23(b)	0.80(b)	0.035	0.040	0.15-0.40	. . .	3.25-3.75	. . .	. . .	. . .
A 204	A	0.25(b)	0.90	0.035	0.040	0.15-0.40	. . .	. . .	0.45-0.60	. . .	. . .
	B	0.27(b)	0.90	0.035	0.040	0.15-0.40	. . .	. . .	0.45-0.60	. . .	. . .
	C	0.28(b)	0.90	0.035	0.040	0.15-0.40	. . .	. . .	0.45-0.60	. . .	. . .
A 225	C	0.25	1.60	0.035	0.040	0.15-0.40	. . .	0.40-0.70	. . .	. . .	V, 0.13-0.18
	D	0.20	1.70	0.035	0.040	0.10-0.50	. . .	0.40-0.70	. . .	. . .	V, 0.10-0.18
A 302	A	0.25(b)	0.95-1.30	0.035	0.040	0.15-0.40	. . .	. . .	0.45-0.60	. . .	. . .
	B	0.25(b)	1.15-1.50	0.035	0.040	0.15-0.40	. . .	. . .	0.45-0.60	. . .	. . .
	C	0.25(b)	1.15-1.50	0.035	0.040	0.15-0.40	. . .	0.40-0.70	0.45-0.60	. . .	. . .
	D	0.25(b)	1.15-1.50	0.035	0.040	0.15-0.40	. . .	0.70-1.00	0.45-0.60	. . .	. . .
A 353	. . .	0.13	0.90	0.035	0.040	0.15-0.40	. . .	8.50-9.50	. . .	. . .	. . .
A 387	2	0.21	0.55-0.80	0.035	0.040	0.15-0.40	0.50-0.80	. . .	0.45-0.60	. . .	. . .

	5	0.15	0.30-0.60	0.040	0.030	0.50	4.00-6.00	. . .	0.45-0.65	. . .	. . .
	7	0.15	0.30-0.60	0.030	0.030	1.00	6.00-8.00	. . .	0.45-0.65	. . .	. . .
	9	0.15	0.30-0.60	0.030	0.030	1.00	8.00-10.00	. . .	0.90-1.10	. . .	. . .
	11	0.17	0.40-0.65	0.035	0.040	0.50-0.80	1.00-1.50	. . .	0.45-0.65	. . .	. . .
	12	0.17	0.40-0.65	0.035	0.040	0.15-0.40	0.80-1.15	. . .	0.45-0.60	. . .	. . .
	21	0.15(b)	0.30-0.60	0.035	0.035	0.50	2.75-3.25	. . .	0.90-1.10	. . .	. . .
	22	0.15(b)	0.30-0.60	0.035	0.035	0.50	2.00-2.50	. . .	0.90-1.10	. . .	. . .
	91	0.08-0.12	0.30-0.60	0.020	0.010	0.20-0.50	8.00-9.50		0.85-1.05	. . .	V, 0.18-0.25; Nb, 0.06-0.10; N, 0.03-0.07; Al, 0.04
A 517	A	0.15-0.21	0.80-1.10	0.035	0.040	0.40-0.80	0.50-0.80	. . .	0.18-0.28	. . .	B, 0.0025
	B	0.15-0.21	0.70-1.00	0.035	0.040	0.20-0.35	0.40-0.65	. . .	0.15-0.25	. . .	B, 0.0005-0.005
	C	0.10-0.20	1.10-1.50	0.035	0.040	0.15-0.30	. . .	. . .	0.20-0.30	. . .	B, 0.001-0.005
	E	0.12-0.20	0.40-0.70	0.035	0.040	0.20-0.35	1.40-2.00	. . .	0.40-0.60	. . .	B, 0.0015, 0.005
	F	0.10-0.20	0.60-1.00	0.035	0.040	0.15-0.35	0.40-0.65	0.70-1.00	0.40-0.60	. . .	B, 0.0005-0.006
	H	0.12-0.21	0.95-1.30	0.035	0.040	0.20-0.35	0.40-0.65	0.30-0.70	0.20-0.30	. . .	B, 0.0005
	J	0.12-0.21	0.45-0.70	0.035	0.040	0.20-0.35	. . .	. . .	0.50-0.65	. . .	B, 0.001-0.005
	M	0.12-	0.45-	0.035	0.040	0.20-	. . .	1.20-	0.45-	. . .	B, 0.001-0.005

		0.21	0.70			0.35		1.50	0.60		
	P	0.12-0.21	0.45-0.70	0.035	0.040	0.20-0.35	0.85-1.20	1.20-1.50	0.45-0.60	. . .	B, 0.001-0.005
	Q	0.14-0.21	0.95-1.30	0.035	0.040	0.15-0.35	1.00-1.50	1.20-1.50	0.40-0.60	. . .	V, 0.03-0.08
	S	0.10-0.20	1.10-1.50	0.035	0.040	0.15-0.40	. . .	. . .	0.10-0.35	. . .	Ti, 0.06; Nb, 0.06
	T	0.08-0.14	1.20-1.50	0.035	0.010	0.40-0.60	. . .	. . .	0.45-0.60	. . .	B, 0.001-0.005; V, 0.03-0.08
A 533	A	0.25	1.15-1.50	0.035	0.040	0.15-0.40	. . .	. . .	0.45-0.60	. . .	. . .
	B	0.25	1.15-1.50	0.035	0.040	0.15-0.40	. . .	0.40-0.70	0.45-0.60	. . .	. . .
	C	0.25	1.15-1.50	0.035	0.040	0.15-0.40	. . .	0.70-1.00	0.45-0.60	. . .	. . .
	D	0.25	1.15-1.50	0.035	0.040	0.15-0.40	. . .	0.20-0.40	0.45-0.60	. . .	. . .
A 542	A	0.15	0.30-0.60	0.025	0.025	0.50	2.00-2.50	0.40	0.90-1.10	0.40	V, 0.03
	B	0.11-0.15	0.30-0.60	0.025	0.15	0.50	2.00-2.50	0.25	0.90-1.10	0.25	V, 0.02
	C	0.10-0.15	0.30-0.60	0.025	0.025	0.13	2.75-325	0.25	0.90-1.10	0.25	V, 0.2-0.3; Ti, 0.015-0.035; B, 0.001-0.003
A 543	B	0.23	0.40	0.035	0.040	0.20-0.40	1.50-2.00	2.60-3.25(b)	0.45-0.60	. . .	V, 0.03
	C	0.23	0.40	0.020	0.020	0.20-0.40	1.20-1.80	2.25-3.25(b)	0.45-0.60	. . .	V, 0.03
A 553	I	0.13	0.90	0.035	0.040	0.15-0.40	. . .	8.50-9.50	. . .	. . .	. . .
	II	0.13	0.90	0.035	0.040	0.15-0.40	. . .	7.50-8.50	. . .	. . .	. . .

A 645	. . .	0.13	0.30-0.60	0.025	0.025	0.20-0.40	. . .	4.75-5.25	0.20-0.35	. . .	Al, 0.02-0.12; N, 0.020
A 734	A	0.12	0.45-0.75	0.035	0.015	0.40	0.90-1.20	0.90-1.20	0.25-0.40	. . .	Al, 0.06
A 735	. . .	0.06	1.20-2.20(b)	0.04	0.025	0.40	. . .	. . .	0.23-0.47	0.20-0.35(c)	Nb, 0.03-0.09
A 736	A	0.07	0.40-0.70	0.025	0.025	0.40	0.60-0.90	0.70-1.00	0.15-0.25	1.00-1.30	Nb, 0.02 min
	C	0.07	1.30-1.65	0.025	0.025	0.40	. . .	0.70-1.00	0.15-0.25	1.00-1.30	Nb, 0.02 min
A782	. . .	0.20	0.7-1.20	0.035	0.040	0.40-0.80	0.50-1.00	. . .	0.20-0.60	. . .	Zr, 0.04-0.12
A832	. . .	0.10-0.15	0.30-0.60	0.025	0.025	0.10	2.75-3.25	. . .	0.90-1.10	. . .	V, 0.20-0.30; Ti, 0.015-0.035; B, 0.001-0.003
A 844	. . .	0.13	0.90	0.020	0.020	0.15-0.40	. . .	8.50-9.50	. . .	. . .	. . .

(a) When a single value is shown, it is a maximum limit, except where specified as a minimum limit.

(b) Limiting values may vary with plate thickness.

(c) When specified

International Designations and Specifications

Most industrialized nations have standards organizations that issue designations and specifications related to steels. Organizations that can assist engineers cross-reference steels from various countries include the American National Standards Institute (ANSI) in the United States and the European Committee for Standardization (CEN) in Brussels, Belgium. The latter is an association of the national standards organizations of 18 countries of the European Union and of the European Free Trade Association. Useful reference sources include:

- A.S. Melilli, Ed., *Comparative World Steel Standards,* ASTM, 1996
- D.L. Potts and J.G. Gensure, *International Metallic Materials Cross-Reference,* Genium Publishing, 1989
- C.W. Wegst, Ed., *Stahlschlüssel: Key to Steel,* 18th ed., Verlag Stahlschlüssel, 1998
- *Worldwide Guide to Equivalent Irons and Steels,* 3rd ed., ASM International, 1992

Mechanical Properties of Carbon and Alloy Steels

Introduction

THE PROPERTIES of carbon and alloy steels are dependent on the relationships between chemical composition, processing, and microstructure. In this article, emphasis is placed on the effect of composition (alloying). The role of processing and microstructure on the properties is described in the Section "Structure/Property Relationships in Irons and Steels" in this Handbook.

Alloying elements are added to ordinary (plain carbon) steels to modify their behavior during thermal processing (heat treatment or thermomechanical processing), which in turn results in improvement of the mechanical and physical properties of the steel. Specifically, alloying additions are made for one or more of the following reasons:

- Improve tensile strength without appreciably lowering ductility
- Improve toughness
- Increase hardenability which permits the hardening of larger sections than possible with plan carbon steels or allows successful quenching with less drastic cooling rates, reducing the hazard of distortion and quench cracking
- Retain strength at elevated temperatures
- Obtain better corrosion resistance
- Improve wear resistance
- Impart a fine grain size to the steel

A semantic distinction can be made between alloying elements and residual elements; the latter are not intentionally added to the steel, but result from the raw materials and steelmaking practices used to produce the steel. Any particular element can be either alloying or residual. For example, some nickel or chromium could come into steel through alloy steel scrap and so be considered residual; however, if either of these elements must be added to a steel to meet the desired composition range it might be considered an alloying element.

Both alloying and residual elements can profoundly affect steel production, manufacture into end products, and service performance of the end product. The effects of one alloying element on a steel may be affected by the presence of other elements; such interactive effects are complex. In addition, the effects of a particular element may be beneficial to steel in one respect but detrimental in others.

Effects of Alloying Elements

General effects of various alloying elements commonly found in carbon and low-alloy steels are summarized below. Composition limits or ranges for these elements are tabulated in the article "Classifications and Designations of Carbon and Alloy Steels" in this Section. Additional information on the effects of alloying elements on the performance of steels can be found in a number of articles contained within this Section (see, for example, the articles "Hardenability of Carbon and Alloy Steels," "Service Characteristics of Carbon and Alloy Steels," and "Corrosion Characteristics of Carbon and Alloy Steels") and in the Sections "Tool Steels" and "Stainless Steels" in this Handbook.

Carbon is the most important single alloying element in steel. It is essential to the formation of cementite (and other carbides), pearlite, spheroidite (an aggregate of spherical carbides in a ferrite matrix), bainite and iron-carbon martensite. Microstructures comprising one or more of these components can provide a wide range of mechanical properties and fabrication characteristics. The relative amounts and distributions of these elements can be manipulated by heat treatment to alter the microstructure, and therefore the properties, of a particular piece of steel. Much of ferrous metallurgy is devoted to the various structures and transformations in iron-carbon alloys; many other alloying elements are considered largely on the basis of their effects on the iron-carbon system.

Assuming that the comparisons are made among steels having comparable microstructures, the strength and hardness are raised as the carbon content is increased; however, toughness and ductility are reduced by increases in carbon content (workability, weldability, and machinability are also deleteriously affected by higher carbon contents). The influence of carbon content on mechanical properties is shown in Fig. 1. The hardness of iron-carbon martensite is increased by raising the carbon content of steel, reaching a maximum at about 0.6% C. Increasing the carbon content also increases hardenability.

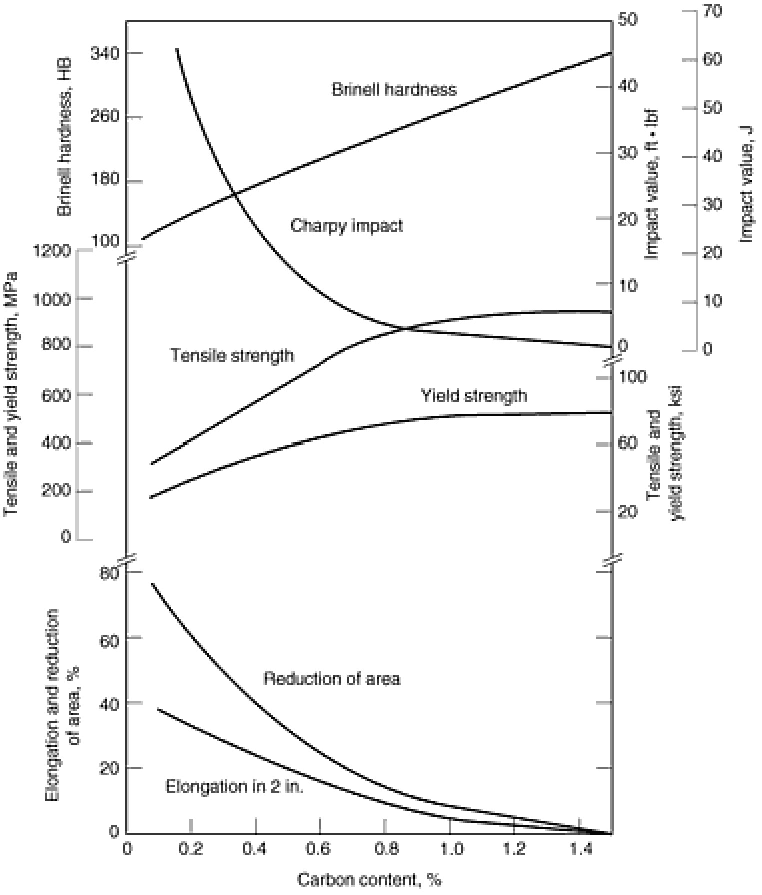


Fig. 1 Variations in average mechanical properties of as-rolled 25 mm (1 in.) diam bars of plain carbon steels as a function of carbon content

The amount of carbon required in the finished steel limits the type of steel that can be made. As the carbon content of rimmed steel increases, surface quality becomes impaired. Killed steels in approximately the 0.15 to 0.30% C content level may have poorer surface quality and require special processing to obtain surface quality comparable to steels with higher or lower carbon content. Carbon has a moderate tendency to segregate, and carbon segregation is often more significant than the segregation of other elements.

Manganese is normally present in all commercial steels. It is important in the manufacture of steel because it deoxidizes the melt and facilitates hot working of the steel by reducing the susceptibility to hot shortness. Manganese also combines with sulfur to form manganese sulfide stringers, which improve the machinability of steel. It contributes to strength and hardness, but to a lesser degree than does carbon; the amount of increase depends on the carbon content. Manganese has a strong effect on increasing the hardenability of a steel.

Manganese has less of a tendency toward macrosegregation than any of the common elements. Steels with more than 0.60% Mn cannot be readily rimmed. Manganese is beneficial to surface quality in all carbon ranges (with the exception of extremely low-carbon rimmed steels.

Silicon is on of the principal deoxidizers used in steelmaking. The amount of this element in a steel, which is not always noted in the chemical composition specifications, depends on the deoxidation practice specified for the product. Rimmed and capped steels contain minimal silicon, usually less than 0.05%. Fully killed steels usually contain 0.15 to 0.30% silicon for deoxidation; if other deoxidants are used, the amount of silicon in the steel may be reduced. Silicon has only a slight tendency to segregate. In low-carbon steels, silicon is usually detrimental to surface quality, and this condition is more pronounced in low-carbon resulfurized grades.

Silicon slightly increases the strength of ferrite, without causing a serious loss of ductility. In larger amounts, it increases the resistance of steel to scaling in air (up to about 260 °C, or 500 °F) and decreases the magnetic hysteresis loss. Such high-silicon steels are generally difficult to process.

Copper has moderate tendency to segregate, and in appreciable amounts, it is detrimental to hot-working operations. Copper adversely affects forge welding, but it does not seriously affect arc or oxyacetylene welding. Detrimental to surface quality, copper exaggerates the surface defects inherent in resulfurized steels. Copper is, however, beneficial to atmospheric corrosion resistance when present in amounts exceeding 0.20%. Steels containing these levels of copper are referred to as weathering steels.

Chromium is generally added to steel to increase resistance to corrosion and oxidation, to increase hardenability, to improve high-temperature strength, or to improve abrasion resistance in high-carbon compositions. Chromium is a strong carbide former. Complex chromium-iron carbides go into solution in austenite slowly; therefore, a sufficient heating time before quenching is necessary.

Chromium can be used as a hardening element and is frequently used with a toughening element such as nickel to produce superior mechanical properties. At higher temperatures, chromium contributes increased strength; it is ordinarily used for applications of this nature in conjunction with molybdenum.

Nickel, when used as an alloying element in constructional steels, is a ferrite strengthener. Because nickel does not form any carbide compounds in steel, it remains in solution in the ferrite, thus strengthening and toughening the ferrite phase. Nickel steels are easily heat treated because nickel lowers the critical cooling rate. In combination with chromium, nickel produces alloy steels with greater hardenability, higher impact strength, and greater fatigue resistance than can be achieved in carbon steels. Nickel alloy steels also have superior low-temperature strength and toughness.

Molybdenum increases the hardenability of steel and is particularly useful in maintaining the hardenability between specified limits. This element, especially in amounts between 0.15 and 0.30%, minimizes the susceptibility of a steel to temper embrittlement. Hardened steels containing molybdenum must be tempered at a higher temperature to achieve the same amount of softening. Molybdenum is unique in the extent to which it increases the high-temperature tensile and creep strengths of steel. It retards the transformation of austenite to pearlite far more than it does the transformation of austenite to bainite; thus, bainite can be produced by continuous cooling of molybdenum-containing steels.

Vanadium is one of the strong carbide-forming elements. It dissolves to some degree in ferrite imparting strength and toughness. Vanadium steels show a much finer structure than steels of a similar composition without vanadium. Vanadium also provides increased hardenability where it is in solution in the austenite prior to quenching, a secondary hardening effect on tempering, and increased hardness at elevated temperatures.

Niobium. Small additions of niobium increase the yield strength and, to a lesser degree, the tensile strength of carbon steel. The addition of 0.20% Nb can increase the yield strength of medium-carbon steel by 70 to 100 MPa (10 to 15 ksi). This increased strength may be accompanied by considerably impaired notch toughness unless special measures are used to refine grain size during hot rolling. Grain refinement during hot rolling involves special thermomechanical processing techniques such as controlled-rolling practices, low finishing temperatures for final reduction passes, and accelerated cooling after rolling is completed.

Aluminum is widely used as a deoxidizer and for control of grain size. When added to steel in specified amounts, it controls austenite grain growth in reheated steels. Of all the alloying elements, aluminum is the most effective in controlling grain growth prior to quenching. Titanium, zirconium, and vanadium are also effective grain growth inhibitors; however, for structural grades that are heat treated (quenched and tempered), these three elements may have adverse effects on hardenability because their carbides are quite stable and difficult to dissolve in austenite prior to quenching.

Boron is added to fully killed steel to improve hardenability. Boron-treated steels are produced in a range of 0.0005 to 0.003%. Whenever boron is substituted in part for other alloys, it should be done only with hardenability in mind because the lowered alloy content may be harmful for some applications. Boron is most effective in lower carbon steels.

Titanium is primarily used as a deoxidizer and helps to limit grain growth in the fully killed steels. Titanium may be added to boron steels because it combines readily with any oxygen and nitrogen in the steel, thereby increasing the effectiveness of the boron in increasing the hardenability of the steel.

Tungsten increases hardness, promotes a fin-grain structure, and is excellent for resisting heat. At elevated tempering temperatures, tungsten forms tungsten carbide, which is very hard and stable. The tungsten carbide helps prevent the steel from softening during tempering. Tungsten is used extensively in high-speed tool steels.

Zirconium inhibits grain growth and is used as a deoxidizer in killed steels. Its primary use is to improve hot-rolled properties in high-strength low-alloy (HSLA) steels. Zirconium in solution also improves hardenability slightly.

Calcium is sometimes used to deoxidize steels. In HSLA steels it helps to control the shape of nonmetallic inclusions, thereby improving toughness. Steels deoxidized with calcium generally have better machinability than do steels deoxidized with silicon or aluminum.

Lead is sometimes added to carbon and alloy steels through mechanical dispersion during teeming for the purpose of improving the machining characteristics of the steels. These additions are generally in the range of 0.15 to 0.35%.

Lead does not dissolve in the steel during teeming but is retained in the form of microscopic globules. At temperatures near the melting point of lead, it can cause liquid-metal embrittlement.

Nitrogen increases the strength, hardness, and machinability of steel, but it decreases the ductility and toughness. In aluminum-killed steels, nitrogen forms aluminum nitride particles that control the grain size of the steel, thereby improving both toughness and strength. Nitrogen can reduce the effect of boron on the hardenability of steels.

Effects of Residual Elements

Any of the alloying elements mentioned above may inadvertently appear in steel as a result of the presence in raw materials used to make the steel. As such, they would be known as "residual" elements. Because of possible undesired (through not necessarily undesirable) effects of these elements on the finished products, most steelmakers are careful to minimize the amount of these elements in the steel, primarily through separation of steel scrap by alloy content.

Several other elements, generally considered to be undesirable impurities, may be introduced into steel from pig iron. For certain specific purposes, however, they may be deliberately added; in this case, they would be considered alloying elements.

Phosphorus increases strength and hardness of steel, but severely decreases ductility and toughness. It increases the susceptibility of medium-carbon alloy steels, particularly straight chromium steels, to temper embrittlement. Phosphorus may be deliberately added to steel to improve its machinability or corrosion resistance.

Sulfur. Increased sulfur content lowers transverse ductility and notch impact toughness but has only a slight effect on longitudinal mechanical properties. Weldability decreases with increasing sulfur content. This element is very detrimental to surface quality, particularly in the lower-carbon and lower-manganese steels. For these reasons only a maximum limit is specified for most steels. The only exceptions is the group of free-machining steels, where sulfur is added to improve machinability; in this case, a range is specified. Sulfur has a greater segregation tendency than do any of the other common elements. Sulfur occurs in steel principally in the form of sulfide inclusions. Obviously a greater frequency of such inclusions can be expected in the resulfurized grades.

Oxygen, which is most likely to be found in rimmed steels, can slightly increase the strength of steel, but seriously reduce toughness.

Hydrogen dissolved in steel during manufacture can seriously embrittle it. This effect is not the same as the embrittlement that results from electroplating or pickling. Embrittlement resulting from hydrogen dissolved during manufacture can cause flaking during cooling from hot rolling temperatures. Dissolved hydrogen rarely affects finished mill products, for reheating the steel prior to hot forming bakes out nearly all of the hydrogen. More detailed information on how hydrogen influences the properties of steels can be found in the Section "Failure Analysis" in this Handbook.

Tin can render steel susceptible to temper embrittlement and hot shortness.

Arsenic and antimony also increase susceptibility of a steel to temper embrittlement.

Properties of Carbon and Alloy Steels

Carbon Steels. The principal factors affecting the properties of the plain carbon steels are carbon content and microstructure. Each type of microstructure is developed to characteristic property ranges by specific processing routes that control and exploit microstructural changes. Processing technologies not only depend on microstructure but are also used to tailor final microstructures. For example, sheet steel formability depends on the single-phase ferritic microstructures of low-carbon cold-rolled and annealed steel, while high strength and wear resistance are enhanced by carefully developed microstructures of very fine carbides in fine martensite in fine-grained austenite of high-carbon hardened steels. (See the Section "Structure/Property Relationships in Irons and Steels" for further details.)

In addition to the predominant effects of carbon content and microstructure, the properties of plain carbon steels may be modified by the effects of residual elements other than the carbon, manganese, silicon, phosphorus, and sulfur that are always present. These incidental elements are usually picked up from the scrap, from the deoxidizers, or from the furnace refractories. The properties of carbon steels may also be affected by the presence of gases, especially oxygen, nitrogen, and hydrogen and their reaction products. The gas content is largely dependent upon the melting, deoxidizing, and pouring practice. The final properties of the plain carbon steels are therefore influenced by the steelmaking practice used in their production.

Thus, the factors governing the properties of a plain carbon steel are primarily its carbon content and microstructure, with the microstructure being determined largely by the composition and the final rolling, forging, or heat-treating operations, and secondarily by the residual alloy, non-metallic, and gas content of the steel, which, in turn, depend on the steelmaking practice.

Figure 1 illustrates the general effect of carbon content when the microstructure and grain size are held reasonably constant. These data are also representative for hot-rolled sheet and strip products. As this figure shows, hardness, tensile strength, and yield strength increase with increasing carbon content, while the elongation, reduction of area, and Charpy impact values decrease sharply. Tables 1 and 2 show both the effects of carbon content and heat treatment on the properties of carbon steels.

Table 1 Mechanical properties of selected carbon and alloy steels in the hot-rolled, normalized, and annealed condition

AISI No.[(a)]	Treatment	Austenitizing temperature		Tensile strength		Yield strength		Elongation, %	Reduction in area, %	Hardness, HB
		°C	°F	MPa	ksi	MPa	ksi			
1015	As-rolled	. . .	. . .	420.6	61.0	313.7	45.5	39.0	61.0	126
	Normalized	925	1700	424.0	61.5	324.1	47.0	37.0	69.6	121
	Annealed	870	1600	386.1	56.0	284.4	41.3	37.0	69.7	111
1020	As-rolled	. . .	. . .	448.2	65.0	330.9	48.0	36.0	59.0	143
	Normalized	870	1600	441.3	64.0	346.5	50.3	35.8	67.9	131
	Annealed	870	1600	394.7	57.3	294.8	42.8	36.5	66.0	111

1022	As-rolled	. . .	. . .	503.3	73.0	358.5	52.0	35.0	67.0	149
	Normalized	925	1700	482.6	70.0	358.5	52.0	34.0	67.5	143
	Annealed	870	1600	429.2	62.3	317.2	46.0	35.0	63.6	137
1030	As-rolled	. . .	. . .	551.6	80.0	344.7	50.0	32.0	57.0	179
	Normalized	925	1700	520.6	75.5	344.7	50.0	32.0	60.8	149
	Annealed	845	1550	463.7	67.3	341.3	49.5	31.2	57.9	126
1040	As-rolled	. . .	. . .	620.5	90.0	413.7	60.0	25.0	50.0	201
	Normalized	900	1650	589.5	85.5	374.0	54.3	28.0	54.9	170
	Annealed	790	1450	518.8	75.3	353.4	51.3	30.2	57.2	149
1050	As-rolled	. . .	. . .	723.9	105.0	413.7	60.0	20.0	40.0	229
	Normalized	900	1650	748.1	108.5	427.5	62.0	20.0	39.4	217
	Annealed	790	1450	636.0	92.3	365.4	53.0	23.7	39.9	187
1060	As-rolled	. . .	. . .	813.6	118.0	482.6	70.0	17.0	34.0	241
	Normalized	900	1650	775.7	112.5	420.6	61.0	18.0	37.2	229
	Annealed	790	1450	625.7	90.8	372.3	54.0	22.5	38.2	179
1080	As-rolled	. . .	. . .	965.3	140.0	586.1	85.0	12.0	17.0	293
	Normalized	900	1650	1010.1	146.5	524.0	76.0	11.0	20.6	293
	Annealed	790	1450	615.4	89.3	375.8	54.5	24.7	45.0	174
1095	As-rolled	. . .	. . .	965.3	140.0	572.3	83.0	9.0	18.0	293
	Normalized	900	1650	1013.5	147.0	499.9	72.5	9.5	13.5	293
	Annealed	790	1450	656.7	95.3	379.2	55.0	13.0	20.6	192

1117	As-rolled	. . .	. . .	486.8	70.6	305.4	44.3	33.0	63.0	143
	Normalized	900	1650	467.1	67.8	303.4	44.0	33.5	63.8	137
	Annealed	855	1575	429.5	62.3	279.2	40.5	32.8	58.0	121
1118	As-rolled	. . .	. . .	521.2	75.6	316.5	45.9	32.0	70.0	149
	Normalized	925	1700	477.8	69.3	319.2	46.3	33.5	65.9	143
	Annealed	790	1450	450.2	65.3	284.8	41.3	34.5	66.8	131
1137	As-rolled	. . .	. . .	627.4	91.0	379.2	55.0	28.0	61.0	192
	Normalized	900	1650	668.8	97.0	396.4	57.5	22.5	48.5	197
	Annealed	790	1450	584.7	84.8	344.7	50.0	26.8	53.9	174
1141	As-rolled	. . .	. . .	675.7	98.0	358.5	52.0	22.0	38.0	192
	Normalized	900	1650	706.7	102.5	405.4	58.8	22.7	55.5	201
	Annealed	815	1500	598.5	86.8	353.0	51.2	25.5	49.3	163
1144	As-rolled	. . .	. . .	703.3	102.0	420.6	61.0	21.0	41.0	212
	Normalized	900	1650	667.4	96.8	399.9	58.0	21.0	40.4	197
	Annealed	790	1450	584.7	84.8	346.8	50.3	24.8	41.3	167
1340	Normalized	870	1600	836.3	121.3	558.5	81.0	22.0	62.9	248
	Annealed	800	1475	703.3	102.0	436.4	63.3	25.5	57.3	207
3140	Normalized	870	1600	891.5	129.3	599.8	87.0	19.7	57.3	262
	Annealed	815	1500	689.5	100.0	422.6	61.3	24.5	50.8	197
4130	Normalized	870	1600	668.8	97.0	436.4	63.3	25.5	59.5	197
	Annealed	865	1585	560.5	81.3	360.6	52.3	28.2	55.6	156

4140	Normalized	870	1600	1020.4	148.0	655.0	95.0	17.7	46.8	302
	Annealed	815	1500	655.0	95.0	417.1	60.5	25.7	56.9	197
4150	Normalized	870	1600	1154.9	167.5	734.3	106.5	11.7	30.8	321
	Annealed	815	1500	729.5	105.8	379.2	55.0	20.2	40.2	197
4320	Normalized	895	1640	792.9	115.0	464.0	67.3	20.8	50.7	235
	Annealed	850	1560	579.2	84.0	609.5	61.6	29.0	58.4	163
4340	Normalized	870	1600	1279.0	185.5	861.8	125.0	12.2	36.3	363
	Annealed	810	1490	744.6	108.0	472.3	68.5	22.0	49.9	217
4620	Normalized	900	1650	574.3	83.3	366.1	53.1	29.0	66.7	174
	Annealed	855	1575	512.3	74.3	372.3	54.0	31.3	60.3	149
4820	Normalized	860	1580	75.0	109.5	484.7	70.3	24.0	59.2	229
	Annealed	815	1500	681.2	98.8	464.0	67.3	22.3	58.8	197
5140	Normalized	870	1600	792.9	115.0	472.3	68.5	22.7	59.2	229
	Annealed	830	1525	572.3	83.0	293.0	42.5	28.6	57.3	167
5150	Normalized	870	1600	870.8	126.3	529.5	76.8	20.7	58.7	255
	Annealed	825	1520	675.7	98.0	357.1	51.8	22.0	43.7	197
5160	Normalized	855	1575	957.0	138.8	530.9	77.0	17.5	44.8	269
	Annealed	815	1495	722.6	104.8	275.8	40.0	17.2	30.6	197
6150	Normalized	870	1600	939.8	136.3	615.7	89.3	21.8	61.0	269
	Annealed	815	1500	667.4	96.8	412.3	59.8	23.0	48.4	197
8620	Normalized	915	1675	632.9	91.8	357.1	51.8	26.3	59.7	183

	Annealed	870	1600	536.4	77.8	385.4	55.9	31.3	62.1	149
8630	Normalized	870	1600	650.2	94.3	429.5	62.3	23.5	53.5	187
	Annealed	845	1550	564.0	81.8	372.3	54.0	29.0	58.9	156
8650	Normalized	870	1600	1023.9	148.5	688.1	99.8	14.0	40.4	302
	Annealed	795	1465	715.7	103.8	386.1	56.0	22.5	46.4	212
8740	Normalized	870	1600	929.4	134.8	606.7	88.0	16.0	47.9	269
	Annealed	815	1500	695.0	100.8	415.8	60.3	22.2	46.4	201
9255	Normalized	900	1650	932.9	135.3	579.2	84.0	19.7	43.4	269
	Annealed	845	1550	774.3	112.3	486.1	70.5	21.7	41.1	229
9310	Normalized	890	1630	906.7	131.5	570.9	82.8	18.8	58.1	269
	Annealed	845	1550	820.5	119.0	439.9	63.8	17.3	42.1	241

Data were obtained from specimens 12.8 mm (0.505 in.) in diameter that were machined from 25 mm (1 in.) rounds.

(a) All grades are fine-grained except for those in the 1100 series, which are coarse grained. Heat-treated specimens were oil quenched unless otherwise indicated.

Table 2 Mechanical properties of selected carbon and alloy steels in the quenched-and-tempered condition

AISI No.(a)	**Tempering temperature**		**Tensile strength**		**Yield strength**		**Elongation, %**	**Reduction in area, %**	**Hardness, HB**
	°C	**°F**	**MPa**	**ksi**	**MPa**	**ksi**			
1030(b)	205	400	848	123	648	94	17	47	495
	315	600	800	116	621	90	19	53	401
	425	800	731	106	579	84	23	60	302
	540	1000	669	97	517	75	28	65	255

	650	1200	586	85	441	64	32	70	207
1040(b)	205	400	896	130	662	96	16	45	514
	315	600	889	129	648	94	18	52	444
	425	800	841	122	634	92	21	57	352
	540	1000	779	113	593	86	23	61	269
	650	1200	669	97	496	72	28	68	201
1040	205	400	779	113	593	86	19	48	262
	315	600	779	113	593	86	20	53	255
	425	800	758	110	552	80	21	54	241
	540	1000	717	104	490	71	26	57	212
	650	1200	634	92	434	63	29	65	192
1050(b)	205	400	1124	163	807	117	9	27	514
	315	600	1089	158	793	115	13	36	444
	425	800	1000	145	758	110	19	48	375
	540	1000	862	125	655	95	23	58	293
	650	1200	717	104	538	78	28	65	235
1050	205	400	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	315	600	979	142	724	105	14	47	321
	425	800	938	136	655	95	20	50	277
	540	1000	876	127	579	84	23	53	262
	650	1200	738	107	469	68	29	60	223

1060	205	400	1103	160	779	113	13	40	321
	315	600	1103	160	779	113	13	40	321
	425	800	1076	156	765	111	14	41	311
	540	1000	965	140	669	97	17	45	277
	650	1200	800	116	524	76	23	54	229
1080	205	400	1310	190	979	142	12	35	388
	315	600	1303	189	979	142	12	35	388
	425	800	1289	187	951	138	13	36	375
	540	1000	1131	164	807	117	16	40	321
	650	1200	889	129	600	87	21	50	255
1095(b)	205	400	1489	216	1048	152	10	31	601
	315	600	1462	212	1034	150	11	33	534
	425	800	1372	199	958	139	13	35	388
	540	1000	1138	165	758	110	15	40	293
	650	1200	841	122	586	85	20	47	235
1095	205	400	1289	187	827	120	10	30	401
	315	600	1262	183	813	118	10	30	375
	425	800	1213	176	772	112	12	32	363
	540	1000	1089	158	676	98	15	37	321
	650	1200	896	130	552	80	21	47	269
1137	205	400	1082	157	938	136	5	22	352

	315	600	986	143	841	122	10	33	285
	425	800	876	127	731	106	15	48	262
	540	1000	758	110	607	88	24	62	229
	650	1200	655	95	483	70	28	69	197
1137(b)	205	400	1496	217	1165	169	5	17	415
	315	600	1372	199	1124	163	9	25	375
	425	800	1103	160	986	143	14	40	311
	540	1000	827	120	724	105	19	60	262
	650	1200	648	94	531	77	25	69	187
1141	205	400	1634	237	1213	176	6	17	461
	315	600	1462	212	1282	186	9	32	415
	425	800	1165	169	1034	150	12	47	331
	540	1000	896	130	765	111	18	57	262
	650	1200	710	103	593	86	23	62	217
1144	205	400	876	127	627	91	17	36	277
	315	600	869	126	621	90	17	40	262
	425	800	848	123	607	88	18	42	248
	540	1000	807	117	572	83	20	46	235
	650	1200	724	105	503	73	23	55	217
1330(b)	205	400	1600	232	1455	211	9	39	459
	315	600	1427	207	1282	186	9	44	402

	425	800	1158	168	1034	150	15	53	335
	540	1000	876	127	772	112	18	60	263
	650	1200	731	106	572	83	23	63	216
1340	205	400	1806	262	1593	231	11	35	505
	315	600	1586	230	1420	206	12	43	453
	425	800	1262	183	1151	167	14	51	375
	540	1000	965	140	827	120	17	58	295
	650	1200	800	116	621	90	22	66	252
4037	205	400	1027	149	758	110	6	38	310
	315	600	951	138	765	111	14	53	295
	425	800	876	127	731	106	20	60	270
	540	1000	793	115	655	95	23	63	247
	650	1200	696	101	421	61	29	60	220
4042	205	400	1800	261	1662	241	12	37	516
	315	600	1613	234	1455	211	13	42	455
	425	800	1289	187	1172	170	15	51	380
	540	1000	986	143	883	128	20	59	300
	650	1200	793	115	689	100	28	66	238
4130(b)	205	400	1627	236	1462	212	10	41	467
	315	600	1496	217	1379	200	11	43	435
	425	800	1282	186	1193	173	13	49	380

	540	1000	1034	150	910	132	17	57	315
	650	1200	814	118	703	102	22	64	245
4140	205	400	1772	257	1641	238	8	38	510
	315	600	1551	225	1434	208	9	43	445
	425	800	1248	181	1138	165	13	49	370
	540	1000	951	138	834	121	18	58	285
	650	1200	758	110	655	95	22	63	230
4150	205	400	1931	280	1724	250	10	39	530
	315	600	1765	256	1593	231	10	40	495
	425	800	1517	220	1379	200	12	45	440
	540	1000	1207	175	1103	160	15	52	370
	650	1200	958	139	841	122	19	60	290
4340	205	400	1875	272	1675	243	10	38	520
	315	600	1724	250	1586	230	10	40	486
	425	800	1469	213	1365	198	10	44	430
	540	1000	1172	170	1076	156	13	51	360
	650	1200	965	140	855	124	19	60	280
5046	205	400	1744	253	1407	204	9	25	482
	315	600	1413	205	1158	168	10	37	401
	425	800	1138	165	931	135	13	50	336
	540	1000	938	136	765	111	18	61	282

	650	1200	786	114	655	95	24	66	235
50B46	205	400	. . .	. . .	. . .	. . .	. . .	. . .	560
	315	600	1779	258	1620	235	10	37	505
	425	800	1393	202	1248	181	13	47	405
	540	1000	1082	157	979	142	17	51	322
	650	1200	883	128	793	115	22	60	273
50B60	205	400	. . .	. . .	. . .	. . .	. . .	. . .	600
	315	600	1882	273	1772	257	8	32	525
	425	800	1510	219	1386	201	11	34	435
	540	1000	1124	163	1000	145	15	38	350
	650	1200	896	130	779	113	19	50	290
5130	205	400	1613	234	1517	220	10	40	475
	315	600	1496	217	1407	204	10	46	440
	425	800	1275	185	1207	175	12	51	379
	540	1000	1034	150	938	136	15	56	305
	650	1200	793	115	689	100	20	63	245
5140	205	400	1793	260	1641	238	9	38	490
	315	600	1579	229	1448	210	10	43	450
	425	800	1310	190	1172	170	13	50	365
	540	1000	1000	145	862	125	17	58	280
	650	1200	758	110	662	96	25	66	235

5150	205	400	1944	282	1731	251	5	37	525
	315	600	1737	252	1586	230	6	40	475
	425	800	1448	210	1310	190	9	47	410
	540	1000	1124	163	1034	150	15	54	340
	650	1200	807	117	814	118	20	60	270
5160	205	400	2220	322	1793	260	4	10	627
	315	600	1999	290	1772	257	9	30	555
	425	800	1606	233	1462	212	10	37	461
	540	1000	1165	169	1041	151	12	47	341
	650	1200	896	130	800	116	20	56	269
51B60	205	400	. . .	. . .	. . .	. . .	. . .	. . .	600
	315	600	. . .	. . .	. . .	. . .	. . .	. . .	540
	425	800	1634	237	1489	216	11	36	460
	540	1000	1207	175	1103	160	15	44	355
	650	1200	965	140	869	126	20	47	290
6150	205	400	1931	280	1689	245	8	38	538
	315	600	1724	250	1572	228	8	39	483
	425	800	1434	208	1331	193	10	43	420
	540	1000	1158	168	1069	155	13	50	345
	650	1200	945	137	841	122	17	58	282
81B45	205	400	2034	295	1724	250	10	33	550

	315	600	1765	256	1572	228	8	42	475
	425	800	1407	204	1310	190	11	48	405
	540	1000	1103	160	1027	149	16	53	338
	650	1200	896	130	793	115	20	55	280
8630	205	400	1641	238	1503	218	9	38	465
	315	600	1482	215	1392	202	10	42	430
	425	800	1276	185	1172	170	13	47	375
	540	1000	1034	150	896	130	17	54	310
	650	1200	772	112	689	100	23	63	240
8640	205	400	1862	270	1669	242	10	40	505
	315	600	1655	240	1517	220	10	41	460
	425	800	1379	200	1296	188	12	45	400
	540	1000	1103	160	1034	150	16	54	340
	650	1200	896	130	800	116	20	62	280
86B45	205	400	1979	287	1641	238	9	31	525
	315	600	1696	246	1551	225	9	40	475
	425	800	1379	200	1317	191	11	41	395
	540	1000	1103	160	1034	150	15	49	335
	650	1200	903	131	876	127	19	58	280
8650	205	400	1937	281	1675	243	10	38	525
	315	600	1724	250	1551	225	10	40	490

	425	800	1448	210	1324	192	12	45	420
	540	1000	1172	170	1055	153	15	51	340
	650	1200	965	140	827	120	20	58	280
8660	205	400	. . .	. . .	. . .	. . .	. . .	. . .	580
	315	600	. . .	. . .	. . .	. . .	. . .	. . .	535
	425	800	1634	237	1551	225	13	37	460
	540	1000	1310	190	1213	176	17	46	370
	650	1200	1068	155	951	138	20	53	315
8740	205	400	1999	290	1655	240	10	41	578
	315	600	1717	249	1551	225	11	46	495
	425	800	1434	208	1358	197	13	50	415
	540	1000	1207	175	1138	165	15	55	363
	650	1200	986	143	903	131	20	60	302
9255	205	400	2103	305	2048	297	1	3	601
	315	600	1937	281	1793	260	4	10	578
	425	800	1606	233	1489	216	8	22	477
	540	1000	1255	182	1103	160	15	32	352
	650	1200	993	144	814	118	20	42	285
9260	205	400	. . .	. . .	. . .	. . .	. . .	. . .	600
	315	600	. . .	. . .	. . .	. . .	. . .	. . .	540
	425	800	1758	255	1503	218	8	24	470

	540	1000	1324	192	1131	164	12	30	390
	650	1200	979	142	814	118	20	43	295
94B30	205	400	1724	250	1551	225	12	46	475
	315	600	1600	232	1420	206	12	49	445
	425	800	1344	195	1207	175	13	57	382
	540	1000	1000	145	931	135	16	65	307
	650	1200	827	120	724	105	21	69	250

Data were obtained from specimens 12.8 mm (0.505 in.) in diameter that were machined from 25 mm (1 in.) rounds.

(a) All grades are fine-grained except for those in the 1100 series, which are coarse grained. Heat-treated specimens were oil quenched unless otherwise indicated.

(b) Water quenched

Alloy steels covered by SAE-AISI designations are not directly produced to specific mechanical properties, but are usually heat treated to achieve the desired properties. For lower strength applications, these steels are usually furnished in the as-rolled, normalized, or annealed condition. Higher strength values may be obtained in the normalized-and-tempered or quenched-and-tempered conditions with the latter heat treatment producing optimal results. Tables 1 and 2 show the effects of heat treatment on the properties of SAE-AISI carbon and alloy steels. Properties of steels produced to meet specific mechanical property requirements (for example ASTM specifications) are discussed in subsequent articles contained in this Section.

Low-Carbon Steel Sheet and Strip

LOW-CARBON STEEL sheet and strip are used primarily in consumer goods. These applications require materials that are serviceable under a wide variety of conditions and that are especially adaptable to low-cost techniques of mass production into articles having good appearance. Therefore, these products must incorporate, in various degrees and combinations, ease of fabrication, adequate strength, excellent finishing characteristics to provide attractive appearance after fabrication, and compatibility with other materials and with various coatings and processes.

The steels used for these products are supplied over a wide range of chemical compositions; however, the vast majority are unalloyed, low-carbon steels selected for stamping applications, such as automobile bodies and appliances. For these major applications, typical compositions are 0.03 to 0.10% C, 0.15 to 0.50% Mn, 0.035% P (max), and 0.04% S (max).

Generally, rimmed (or capped) ingot cast steel has been used because of its lower price. More recently, these steels have been replaced by killed steels produced by the continuous casting process. This process is inherently suited to the production of killed steels. Where strain aging is to be avoided and/or when exceptional formability is required, steel killed with aluminum, regardless of the method of casting or manufacture, is preferred. Further details regarding steelmaking and deoxidation practice are given in the Section "Steelmaking Practices and Their Influence on Properties" in this Handbook.

The width differentiation between sheet and strip made of plain carbon steel depends on the rolling process. It should be noted that both sheet and strip can be purchased as either cut lengths or coils. The standard dimensional tolerances for plain carbon steel strip are more restrictive than those for sheet. Standard size ranges of plain carbon steel sheet and strip are given in Table 1. Typical characteristics of the various qualities of these products are listed in Tables 2(a) and 2(b).

Table 1 Standard sizes of low-carbon sheet and strip

Product	**Thickness**		**Width**		**Other limitations**	**Specification symbol (ASTM No.)**	
	mm	**in.**	**mm**	**in.**		**Metric units**	**English units**
Hot-rolled sheet	1.2-6.0	0.045-0.230 incl	>300-1200 incl	>12-48 incl	Coils and cut lengths	A 569M, A 621M, or A 622M	A 569, A 621, or A 622
	1.2-4.5	0.45-0.180 incl	>1200	>48	Coils and cut lengths	A 569M, A 621M, or A 622M	A 569, A 621, or A 622
	6.0-12.5	0.230-0.500 incl	>300-1200 incl	>12-48 incl	Coils only	A 635M	A 635
	4.5-12.5	0.180-0.500 incl	>1200-1800 incl	>48-72 incl	Coils only	A 635M	A 635
Hot-rolled strip	1.2-5.0	0.45-0.203 incl	≤200	≤6	Coils and cut lengths	A 569M, A 621M, or A 622M	A 569, A 621, or A 622
	1.2-6.0	0.045-0.229 incl	>200-300 incl	>6-12 incl	Coils and cut lengths	A 569M, A 621M, or A 622M	A 569, A 621, or A 622
	6.0-12.5	0.230-0.500 incl	>200-300 incl	>8-12 incl	Coils only	A 635M	A 635
Cold-rolled sheet	0.35-2.0	0.014-0.082 incl	>50-300 incl	>2-12 incl	(a)	A 366M, A 619M, or A 620M	A 366, A 619, or A 620
	≥0.35	>0.014	>300	>12	(b)	A 366M, A 619M, or A 620M	A 366, A 619, or A 620
Cold-rolled strip	≤6.0	≤0.250	>12-600 incl	>0.50-23.9 incl	(c)	A 109M	A 109

(a) Cold-rolled sheet, coils, and cut lengths, slit from wider coils with cut edge (only) thickness 0.356-2.08 mm (0.014-0.082 in.) and 0.25% C (max) by cost analysis.

(b) When no special edge or finish (other than matte, commercial bright, or luster) is required and/or single-strand rolling of widths under 610 mm (24 in.) is not required.

(c) Width 51-305 mm (2-12 in.) with thicknesses of 0.356-2.08 mm (0.014-0.082 in.) are classified as sheet when slit from wider coils, have a cut edge only, and contain 0.25% C (max) by cost analysis.

Table 2(a) Summary of available types of hot-rolled and cold-rolled plain carbon steel sheet and strip

Quality or temper	Applicable basic specification number	SAE-AISE grade designation	Surface finish			
			Temper-rolled; for exposed parts[(a)]		Annealed last; for unexposed parts[(a)]	
			Description	Symbol	Description	Symbol
Hot-rolled sheet						
Commercial quality	A 569, A 635	1008-1012	As-rolled (black)	A	As-rolled (black)	A
			Pickled--dry	P	Pickled--dry	P
			Pickled and oiled	O	Pickled and oiled	O
Drawing quality	A 621	1006-1008	As-rolled (black)	A	As-rolled (black)	A
			Pickled--dry	P	Pickled--dry	P
			Pickled and oiled	O	Pickled and oiled	O
Drawing quality, special killed	A 622	1006-1008	As-rolled (black)	A	As-rolled (black)	A
			Pickled--dry	P	Pickled--dry	P
			Pickled and oiled	O	Pickled and oiled	O
Hot-rolled strip						
Commercial quality	A 569	1008-1012	As-rolled (black)	A	As-rolled (black)	A
			Pickled--dry	P	Pickled--dry	P
			Pickled and oiled	O	Pickled and oiled	O

Drawing quality	A 621	1006-1008	As-rolled (black)	A	As-rolled (black)	A
			Pickled--dry	P	Pickled--dry	P
			Pickled and oiled	O	Pickled and oiled	O
Drawing quality, special killed	A 622	1006-1008	As-rolled (black)	A	As-rolled (black)	A
			Pickled--dry	P	Pickled--dry	P
			Pickled and oiled	O	Pickled and oiled	O
Cold-rolled sheet						
Commercial quality	A 366	1008-1012	Matte	E	Matte	U
			Commercial bright	B		
			Luster	L		
Drawing quality	A 619	1006-1008	Matte	E	Matte	U
			Commercial bright	B		
			Luster	L		
Drawing quality, special killed	A 620	1006-1008	Matte	E	Matte	U
			Commercial bright	B		
			Luster	L		
Cold-rolled strip						
Temper description numbers 1, 2, 3, 4, 5	A 109	(b)	Matte	1	Matte	1
			Regular bright	2	Regular bright	2

			Best bright	3	Best bright	3

(a) See Table 2(b) for a description of the surface finish listed.

(b) Produced in five tempers with specific hardness and bend test limits; composition subordinate to mechanical properties.

Table 2(b) Selection and specification of surface condition for plain carbon steel sheet

Specification symbol	Description of surface	Surface described applicable to
U[a]	Surface finish as normally used for unexposed automotive parts. Matte appearance. Normally annealed last	Cold-rolled sheet
E[b]	Surface finish as normally used for exposed automotive parts that require a good painted surface. Free from strain markings and fluting. Matte appearance. Temper rolled	Cold-rolled sheet
B	Same as above, except commercial bright appearance	Cold-rolled sheet
L	Same as above, except luster appearance	Cold-rolled sheet
1	No. 1 or dull finish (no luster). Especially suitable for lacquer or paint adhesion. Facilitates drawing by reducing the contact friction between the die and the metal	Cold-rolled strip
2	No. 2 or regular bright finish (moderately smooth). Suitable for many applications, but not generally applicable for parts to be plated, unless polished and buffed	Cold-rolled strip
3	No. 3 or best bright finish (relatively high luster). Particularly suitable for parts to be plated	Cold-rolled strip
A	As-rolled or black (oxide or scale not removed)	Hot-rolled sheet and strip
P	Pickled (scale removed), not oiled	Hot-rolled sheet and strip
O	Same as above, except oiled	Hot-rolled sheet and strip

(a) U, unexposed; also designated as class 2, cold-rolled sheet.

(b) E, exposed; also designated as class 1, cold-rolled sheet

Production of Sheet and Strip

Most cold-rolled low-carbon steel sheet is available in two classes (Table 2(a)). Class 1 (temper rolled) is intended for applications where surface appearance is important and where specified surface and flatness requirements must be met. Class 2 is a product intended for applications where appearance is less important. Cold-rolled low-carbon steel strip is available in five hardness tempers ranging from full hard to dead soft (Table 3).

Table 3 Mechanical properties of cold-rolled low-carbon steel strip (ASTM A 109)

Temper	**Hardness requirements, HRB**	**Bent test requirements**[(a)]	**Approximate tensile strength**		**Elongation in 50 mm (2 in.)**[(b)]**, %**
			MPa	**ksi**	
No. 1 (hard)	90 minimum[(c)], 84 minimum[(d)]	No bending in either direction	550-690	80-100	. . .
No. 2 (half-hard)	70-85[(d)]	90° bend across rolling direction around a l*t* radius	380-520	55-75	4-16
No. 3 (quarter-hard)	60-75[(e)]	180° bend across rolling direction and 90° bend along rolling direction, both around a l*t* radius	310-450	45-65	13-27
No. 4 (skin rolled)	65 maximum[(e)]	Bend flat on itself in any direction	290-370	42-54	24-40
No. 5 (dead	55 maximum[(e)]	Bend flat on itself in any direction	260-	38-50	33-45

(a) *t* = thickness of strip.

(b) For strip 1.27 mm (0.050 in.) thick.

(c) For strip of thickness 1.02-1.78 mm exclusive (0.040-0.070 in. exclusive).

(d) For strip of thickness 1.78-6.35 mm exclusive (0.070-0.250 in. exclusive).

(e) For strip of thickness 1.02-6.35 mm exclusive (0.040-0.250 in. exclusive)

Quality Descriptors for Carbon Steels

The descriptors of quality used for hot-rolled plain carbon steel sheet and strip and cold-rolled plain carbon steel sheet include structural quality, commercial quality, drawing quality, and drawing quality, special killed (Table 2(a)). Some of the as-rolled material made to these qualities is subject to surface disturbances known as coil breaks, fluting, and stretcher strains; however, fluting and stretcher strains will not be produced during subsequent forming if the material is temper rolled and/or roller leveled immediately prior to forming. It should be noted that any beneficial effects of roller leveling deteriorate rapidly in nonkilled steel. In addition to the requirements listed below for the various qualities of plain carbon steel sheet and strip, special soundness can also be specified.

Commercial quality (CQ) plain carbon steel sheet and strip are suitable for moderate forming; material of this quality has sufficient ductility to be bent flat on itself in any direction in a standard room-temperature bend test. Commercial quality material is not subject to any other mechanical test requirements, and it is not expected to have exceptionally uniform chemical composition or mechanical properties. However, the hardness of cold-rolled CQ sheet is ordinarily less than 60 HRB at the time of shipment.

Drawing Quality. When greater ductility or more uniform properties than those afforded by commercial quality are required, drawing quality (DQ) is specified. Drawing quality material is suitable for the production of deep-drawn parts and other parts requiring severe deformation. When the deformation is particularly severe or resistance to stretcher strains is required, drawing quality, special killed (DQSK) is specified.

Structural quality (SQ), formerly called physical quality (PQ), is applicable when specified strength and elongation values are required in addition to bend tests (Table 4). Minimum values of tensile strength ranging up to 690 MPa (100 ksi) in hot-rolled sheet and strip and up to 1035 MPa (150 ksi) in cold-rolled sheet are available. Cold-rolled strip, which does not have a quality descriptor, is available in five tempers that conform to specified Rockwell hardness ranges and bend test requirements (Table 3).

Table 4 Tensile requirements for structural quality low-carbon steel

Class or grade	Yield strength, minimum		Tensile strength, minimum		Elongation in 50 mm (2 in.), minimum, %
	MPa	ksi	MPa	ksi	
Structural quality hot-rolled sheet and strip in cut lengths or coils (ASTM A 570)[a]					
30	205	30	340	49	25.0[b]
33	230	33	360	52	23.0[b]
36	250	36	365	53	22.0[b]
40	275	40	380	55	21.0[b]
45	310	45	415	60	19.0[b]
50	345	50	450	65	17.0[b]
55	380	55	480	70	15.0[b]
Structural quality cold-rolled sheet in cut lengths or coils (ASTM A 611)[a]					
A	170	25	290	42	26
B	205	30	310	45	24
C	230	33	330	48	22

D, types 1 and 2	275	40	360	52	20
E	550[(c)]	80[(c)]	565	82	. . .

(a) For coil products, testing by the producer is limited to the end of the coil. Results of such tests must comply with the specified values; however, design considerations must recognize that variation in strength levels can occur throughout the untested portions of the coil, though generally these levels will not be less than 90% of the minimum values specified.

(b) At thickness, *t*, of 2.5-5.9 mm (0.097-0.230 in.).

(c) On this full-hard product, the yield point approaches the tensile strength; because there is no halt in the gage or drop in the beam, the yield point shall be taken as the stress at 0.5% elongation, under load

Mechanical Properties

The commonly measured tensile properties of plain carbon steel sheet and strip are not readily related to their performance in fabrication; the relationship between formability and values of the strain-hardening exponent, *n*, and the plastic strain ratio, *r* (determined in tensile testing), is discussed in the Section "Mechanical, Wear, and Corrosion Testing" in this Handbook. The mechanical properties of commercial quality, drawing quality, and drawing quality, special killed sheet and strip are not ordinarily used in specifications unless special strength properties are required in the fabricated product. As a matter of general interest, however, the ranges of mechanical properties typical of sheet produced by three mills in these qualities are shown in Fig. 1. The bands would be wider if the product of the entire industry were represented. It should be noted that the ranges are broader and the sheet harder for the hot-rolled than for the cold-rolled materials.

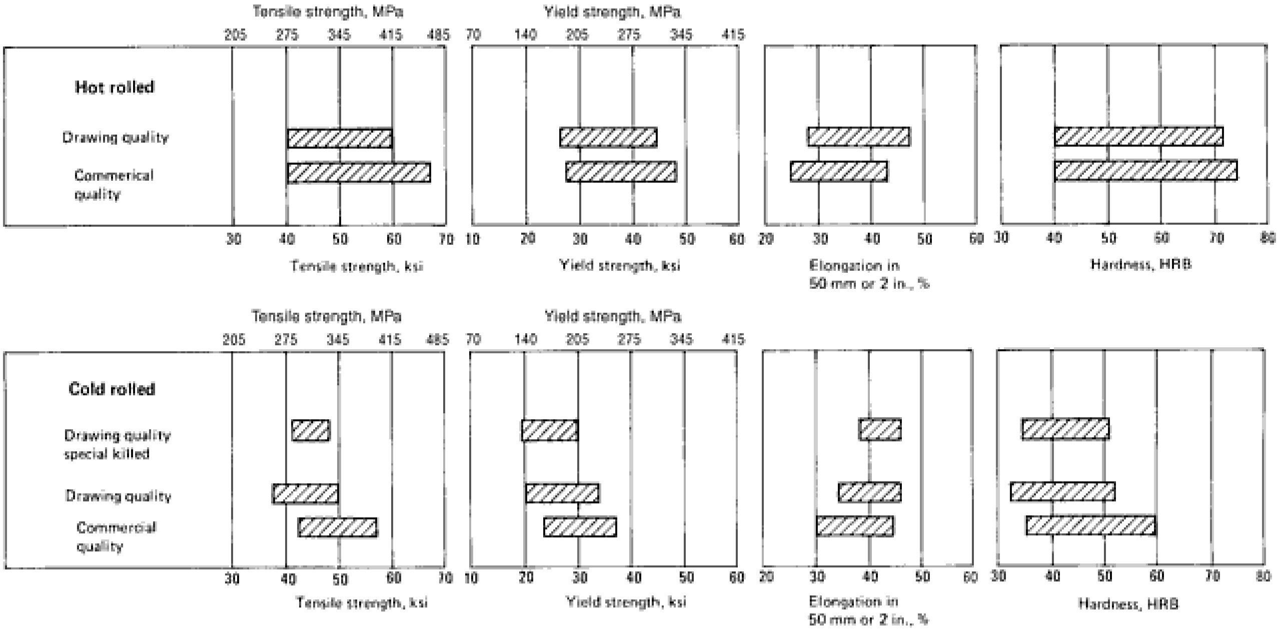


Fig. 1 Typical mechanical properties of low-carbon steel sheet shown by the range of properties in steel furnished by three mills. Hot-rolled sheet thickness from 1.519 to 3.416 mm (0.0598 to 0.1345 in., or 16 to 10 gage); cold-rolled sheet thickness from 0.759 to 1.519 mm (0.0299 to 0.0598 in., or 22 to 16 gage). All cold-rolled grades include a temper pass. All grades were rolled from rimmed steel except the one labeled special killed. See Table 4 for the mechanical properties of structural (physical) quality sheet.

Modified Low-Carbon Steel Sheet and Strip

In addition to the low-carbon steel sheet and strip products already discussed in this article, there are numerous additional products available that are designed to satisfy specific customer requirements. These products are often made with low-carbon steels having chemical compositions slightly modified from those discussed earlier. For example, in SQ steels, alloying additions of manganese and phosphorus are used to increase strength by substitutional solid-solution strengthening: approximately 3 MPa (0.4 ksi) per 0. 1% Mn, and 7 MPa (1 ksi) per 0.0 1% P. Hot-rolled SQ steels contain from 0.90 to 1.35% max Mn and 0.035% max P. Cold-rolled SQ steels contain 0.60 to 0.90% max Mn and 0.035 to 0.20% P. Carbon contents for SQ steels are generally 0.20 to 0.25%.

Interstitial-Free Steels. In IF steels, which are also referred to as extra deep drawing quality (EDDQ), the elimination of interstitials (carbon and nitrogen) is accomplished by adding sufficient amounts of carbide/nitride-forming elements (generally titanium and/or niobium) to tie up carbon and nitrogen completely, the levels of which can be reduced to less than 50 ppm by modem steelmaking/casting practices, including vacuum degassing.

Steels with very low interstitial content exhibit excellent formability with low yield strength (138 to 165 MPa, or 20 to 24 ksi), high elongation (41 to 45%), and good deep drawability. With the addition of carbonitride-forming elements, the deep drawability and the nonaging properties are further improved.

Bake-hardening (BH) steels are characterized by their ability to exhibit an increase in yield strength due to carbon strain aging during paint-baking operations at moderate temperature (125 to 180 °C, or 260 to 355 °F). Bake hardening has little effect on tensile strength. Bake-hardening steels are finding increased usage in automotive outer-body applications (hoods, doors, fenders) to achieve an improvement in dent resistance and, in some cases, a sheet thickness reduction as well.

The bake-hardening behavior is dependent on steel chemistry and processing, in addition to the amount of forming strain and paint-baking conditions (temperature and time). Steels that exhibit bake-hardening behavior include plain low-carbon steels (continuously annealed or batch annealed), IF steels (continuously annealed), and dual-phase steels (continuously annealed).

Current automotive specifications for BH steels can be categorized according to those that specify a minimum yield strength level or a minimum bake-hardening increment, in the formed (strained) plus baked condition. The conventional test for determining bake-hardenability characteristics involves a 2% tensile prestrain, followed by baking at 175 ± 5 °C (345 ± 10 °F). The resulting increase in yield strength measures the bake hardenability of the material.

While all the specifications call for a minimum yield strength level in the as-received (that is, prior to forming) condition, some also require a minimum yield strength after baking the as-received material in the absence of any tensile prestrain. The as-received yield strength is in the range 210 to 310 MPa (30 to 45 ksi) (compared with about 175 MPa, or 25 ksi, for DQSK), while the final yield strength, that is, after 2% prestrain plus bake, ranges between 280 and 365 MPa (40 to 53 ksi) (compared with about 225 MPa, or 33 ksi, for DQSK).

Alloy Steel Sheet and Strip

ALLOY STEEL sheet and strip are used primarily for those special applications that require the mechanical properties normally obtained by heat treatment. A sizable selection of the standard alloy steels is available as sheet and strip, either hot rolled or cold rolled. The most commonly available alloys are listed in Table 5. In addition to standard low-alloy steels, high-strength low-alloy (HSLA) and dual-phase steels are available as sheet or strip for applications requiring tensile strengths in the range of 290 to 760 MPa (42 to 110 ksi). These steels are discussed in the article "High-Strength Structural and High-Strength Low-Alloy Steels" in this Section.

Table 5 Standard alloy steels available as sheet and strip

SAE or AISI designation	Chemical composition ranges and limits (heat analysis)[(a)], %							
	C	Mn	P	S	Si[(b)]	Ni	Cr	Mo
4118	0.18-0.23	0.70-0.90	0.035	0.040	0.15-0.30	. . .	0.40-0.60	0.08-0.15
4130	0.28-0.33	0.40-0.60	0.035	0.040	0.15-0.30	. . .	0.80-1.10	0.15-0.25
4140	0.38-0.43	0.75-1.00	0.035	0.040	0.15-0.30	. . .	0.80-1.10	0.15-0.25
4340	0.38-0.43	0.60-0.80	0.035	0.040	0.15-0.30	1.65-2.00	0.70-0.90	0.20-0.30
5140	0.38-0.43	0.70-0.90	0.035	0.040	0.15-0.30	. . .	0.70-0.90	. . .
5150	0.48-0.53	0.70-0.90	0.035	0.040	0.15-0.30	. . .	0.70-0.90	. . .
5160	0.55-0.65	0.75-1.00	0.035	0.040	0.15-0.30	. . .	0.70-0.90	. . .
8615	0.13-0.18	0.70-0.90	0.035	0.040	0.15-0.30	0.40-0.70	0.40-0.60	0.15-0.25

(a) The chemical ranges and limits shown are subject to product analysis tolerances. See ASTM A 505.

(b) Other silicon ranges are available. Consult the producer.

Quality Descriptors

As it is used for steel mill products, the term "quality" relates to the general suitability of the mill product to make a given class of parts. For alloy steel sheet and strip, the various quality descriptors imply certain inherent characteristics, such as degree of internal soundness and relative freedom from harmful surface imperfections.

The quality descriptors used for alloy steel sheet and plate include regular quality, drawing quality, and aircraft quality, which are covered by ASTM specifications. The general requirements for these qualities are covered by ASTM A 505. Additional qualities include bearing quality and aircraft structural quality. Aircraft quality requirements are also covered in AMS specifications.

Mill Heat Treatment

Hot-rolled regular-quality alloy steel sheet and strip normally are available from the producer either as rolled or as heat treated. Standard mill heat treated conditions are: annealed, normalized, and normalized and tempered. Cold-rolled regular-quality product normally is available only in the annealed condition.

Precoated Steel Sheet

STEEL SHEET frequently is coated in coil form before fabrication either by the steel mills or by specialists called coil coaters.

The basic types of precoating include metallic, conversion, preprimed, and prepainted finishing. Metallic coating may be done with zinc, aluminum, tin, terne metal, or combinations of metals such as aluminum and zinc. Conversion coatings are completed with phosphates, and preprimed finishes are done with zinc chromate and zinc-rich coatings. Prepainting consists of applying an organic paint system to steel sheet on a coil coating line either at a mill or at a coil coater.

Zinc Coatings

Metallic zinc is applied to iron and steel by one of three processes: hot dip galvanizing, electrogalvanizing, or zinc spraying. Most galvanized steel sheet is coated by the hot dip process.

Coating thickness is a key factor in determining coated product performance. In general, thicker coatings provide greater corrosion protection, whereas thinner coatings tend to give better formability and weldability. The amount of coating can also be expressed in terms of mass per unit area. This is determined by weighing a section of the coated product, stripping the coating in an acid solution, and weighing again. Table 6 summarizes coating thickness and mass called for by ASTM specifications. The coating thickness is usually expressed in terms of the coating on one side, whereas the mass is usually given as the sum of the coating on both sides.

Table 6 Nominal coating mass and thickness for continuous hot dip coatings on steel sheet

Type of coating[(a)]	**Designation**	**Coating mass**[(b)]**, g/m^2**	**Coating thickness**[(c)]**, μm**
Zinc (A 525)	Z1100	1100	78
	900	900	64
	700	700	50
	600	600	42
	450	450	32
	350	350	25
	275	275	19
	180	180	13
	90	90	6
	001	[(d)]	[(d)]
Zinc-iron (A 525)	ZF180	180	11

	120	120	9
	100	100	7
	75	75	5
	001	(d)	(d)
Aluminum (A 463) type 1	T1 40	120	20
	25	75	12
Aluminum (A 463) type 2	T2 100	305	48
	65	195	30
	LC	(d)	(d)
Zn-5Al (A 575)	ZGF 700	700	48
	600	600	41
	450	450	31
	350	350	24
	275	275	19
	225	225	15
	180	180	12
	135	135	9
	90	90	6
	001	(d)	(d)
Zn-55Al (A 792)	AZ 180	180	24
	165	165	22

	150	150	20
Lead-tin (A 308)	LT 110	336	15
	85	259	12
	55	168	8
	40	122	6
	35	107	5
	25	76	3
	01	(d)	(d)

All values are based on specified triple-spot minima.

(a) ASTM specifications as given in *Coated Steel Products,* Vol 01.06, *Annual Book of ASTM Standards,* ASTM.

(b) Two sides.

(c) One side. Calculated from densities in g/cm^3 as follows: zinc and zinc-iron, 7.07; aluminum type 1, 3.017; aluminum type 2, 3.21; Zn-5Al, 6.87; Zn-55Al, 3.70; lead-tin, 11.08.

(d) No minimum

Hot dip galvanizing is a process in which an adherent, protective coating of zinc and iron-zinc alloys is developed on the surfaces of iron and steel products by immersing them in a bath of molten zinc. Most zinc coating of steel sheet is done by this process, usually on a continuous galvanizing line.

A typical hot dip galvanized coating consists of a series of layers. Starting from the basis steel at the bottom of the coating, each successive layer contains a higher proportion of zinc until the outer layer, which is relatively pure zinc, is reached. There is, therefore, no discrete line of demarcation between the iron and zinc, but a gradual transition through the series of iron-zinc alloys that provide a powerful bond between the basis metal and the coating.

Electrogalvanizing. Very thin formable zinc coatings ideally suited for deep drawing or painting can be obtained on steel products by electrogalvanizing. Zinc is electrodeposited on a variety of mill products, sheet, wire and, in some instances, pipe. Electrogalvanizing of sheet and wire in coil form produces a thin, uniform coating of pure zinc.

Electrodeposited zinc coatings are simpler in structure than hot dip galvanized coatings. They are composed of pure zinc, have a homogeneous structure, and are highly adherent. These coatings are not generally as thick as those produced by hot dip galvanizing. However, they do give good corrosion-free service. Coating thicknesses/masses range from 4 to 14 μm (30 to 100 g/m^2) per side, although the most common coating thicknesses/masses are 8 and 10 μm (60 and 70 g/m^2). For nonautomotive applications, a thickness/mass of as low as 1.5 μm (10 g/m^2) can be used. Electrodeposited zinc is considered to adhere to steel as well as any other metallic coating. Because of its excellent adhesion, electrogalvanized coils of steel sheet and wire have good working properties, and the coating remains intact after severe deformation. Good adhesion depends on very close physical conformity of the coating with the basis metal. Therefore, particular care must be taken during initial cleaning. Electrodeposition also affords a means of applying zinc coatings to finished parts that cannot be predipped. It is especially useful where a high processing temperature could injure the part. One advantage of electrodeposition is that it can be done cold and thus does not change the mechanical properties of the steel.

Zinc spraying consists of projecting atomized particles of molten zinc onto a prepared surface. Three types of spraying pistols are in commercial use today: the molten metal pistol, the powder pistol, and the wire pistol. The sprayed coating is slightly rough and slightly porous; the specific gravity of a typical coating is approximately 6.35, compared with 7.1 for cast zinc. This slight porosity does not affect the protective value of the coating, because zinc is anodic to steel. The zinc corrosion products that form during service fill the pores of the coating, giving a solid appearance. The slight roughness of the surface makes it an ideal basis for paint, when properly pretreated.

Chromate Passivation. Several types of finishes can be applied to zinc-coated surfaces to provide extra corrosion resistance. The simplest type of finish applicable to fresh zinc surfaces is a chromate passivation treatment. It is equally suitable for use on hot dip galvanized, zinc-sprayed, and zinc-plated articles. Usually, the treatment consists of simply cleaning the articles and then dipping them in a chromic acid or sodium dichromate solution at about 20 to 30 °C (68 to 86 °F), followed by rinsing in cold fresh water and drying in warm air.

Anodizing of galvanized steel produces a surface that exhibits exceptional resistance to corrosion, wear, heat, and abrasion. The anodized film is an electrical insulator. The film is formed by immersing finished parts in a simple electrolyte and applying an increasing voltage for up to 10 min. A nonreflective functional coating, anodized zinc demonstrates superior properties when compared with chromate conversion coatings. The anodized zinc coatings range from 25 to 33 μm (1.0 to 1.3 mils) in thickness and will not deteriorate at temperatures up to the melting point of zinc.

Painting. The selection of galvanized steel as a material for barns, buildings, roofs, sidings, appliances and many hardware items is based on the sacrificial protection plus the barrier coating afforded the basis metal by zinc coating. For additional protection and pleasing appearance, paint coatings are often applied to the galvanized steel.

Weldability. Direct spot welding is recommended for zinc-coated steel, which may be either hot dip galvanized or electroplated, because the shunting current associated with series welding, when added to the higher-than-normal current needed to weld zinc-coated steel, results in excessive electrode heating and short electrode life.

Weldability of thin sheets electroplated with zinc decreases as the coating thickness increases, in the range from 0.005 to 0.025 mm (0.0002 to 0.001 in.). However, as sheet thickness increases above 1.5 mm (0.060 in.), weldability increases regardless of coating thickness. The welding behavior of hot dip galvanized steel is affected by the thickness and uniformity of the zinc-iron alloy layer, as well as the thickness of unalloyed zinc.

Aluminum Coatings

Aluminized (aluminum-coated) steel sheet is used for applications where heat resistance, heat reflectivity, or resistance to corrosion are required in an aesthetically pleasing, economical sheet. Aluminum coating is done on continuous lines similar to those used for hot dip galvanizing of steel sheet. Cold rolled steel sheet is hot dipped into molten aluminum or an aluminum alloy containing 5 to 11% Si. The coating consists of two interfacial layers. Between the exterior layer of aluminum-silicon alloy and the steel basis metal, an aluminum-iron-silicon alloy layer is formed. This alloy can significantly affect the ductility, adhesion, uniformity, smoothness, and appearance of the surface and is controlled for optimum properties.

Coating Thickness. Two kinds of aluminum coating are produced (Table 6). Type 2 is a thicker coating (typically 30 to 50 μm) that is applied by dipping in an unalloyed aluminum bath. This product is used for outdoor construction applications such as roofing, culverts, and silos that require resistance to atmospheric corrosion and have limited formability requirements.

Type 1 aluminum coating is a thinner, aluminum-silicon alloy coating intended primarily for applications requiring formability and resistance to high temperatures, such as automobile exhaust components. Type 1 aluminum coatings are also applied to improve appearance. For most uses, the usual thickness of a Type 1 coating (Class 40) is about 20 to 25 μm (0.8 to 1 mil). When maximum formability is a critical requirement, a thinner 12 μm (Class 25) coating is specified.

Corrosion Resistance. Aluminum's value as a protective coating for steel sheet lies principally in its inherent corrosion resistance. In most environments, the long-term corrosion rate of aluminum is only about 15 to 25% of that of zinc. Generally, the protective value of an aluminum coating on steel is a function of coating thickness. The coating tends to remain intact and thus provides long-term protection.

Aluminum coatings do not provide sacrificial protection in most environments, particularly in atmospheric exposure.

Heat Resistance. Aluminum-coated sheet steel has excellent resistance to high-temperature oxidation. At surface temperatures above about 510 °C (950 °F), the aluminum coating protects the steel basis metal against oxidation without discoloration. Between 510 and 675 °C (950 and 1250 °F), the coating provides protection to the steel, but some darkening may result from the formation of aluminum-iron-silicon alloy. The alloy is extremely heat resistant, but on long exposure, the coating may become brittle and spall at temperatures above 675 °C (1250 °F) due to a different coefficient of expansion from that of the steel.

Weldability. Aluminum-coated steel sheet can be joined by electric resistance welding (spot welding or seam welding). It also can be metal-arc welded, flash welded, or oxyacetylene welded. Thorough removal of grease, oil, paint, and dirt followed by wire brushing is recommended before joining. Special fluxes are required for metal arc and oxyacetylene welding. During spot welding, electrodes tend to pick up aluminum, and the tips must be dressed more frequently than during spot welding of uncoated steel. Also, current density should be higher.

Tin Coatings

Tin coatings are applied to steel sheet either by electrolytic deposition or by immersion in a molten bath of tin (hot dip process). Hot dip tin coatings are applied to provide nontoxic, protective and decorative coating of food-handling, packaging, and dairy equipment, and to facilitate soldering of components used in electronic and electrical equipment. In the United States, hot dip tin coating has been replaced by electrolytic tin coating.

Electrolytic tin-coated steel sheet is used where solderability, appearance, or corrosion resistance under certain conditions is important, such as in electronic equipment, food-handling and processing equipment, and laboratory clamps. It is generally produced with a matte finish formed by applying the coating to basis metal sheet called "black plate," which has a dull surface texture, and leaving the coating unmelted. It can also be produced with a bright finish formed by applying the coating to basis metal having a smooth surface texture and then melting the coating. Electrolytic tin-coated sheet is usually produced in nominal thicknesses from 0.38 to 0.84 mm (0.015 to 0.033 in.) and in widths from 300 to 910 mm (12 to 36 in.).

Tin coatings are of the order of 0.4 to 1.5 μm thick, although they are usually expressed in terms of coating mass. Present values range from 0.5 to 11 g/m^2 on each surface. In the United States, tin coatings have numbers (Table 7) that designate the total weight of tin (i.e., the weight of the tin on the two sides per base box, a measure of surface area equal to 31,360 in.^{2}, originally defined as 112 sheets, 14 by 20 in.). Presently there is a tendency, for economical and technological reasons, to apply lower-tin coatings, most commonly No. 20 or 25 (2.2 or 2.8 g/m^2).

Table 7 Electrolytic tin coating weight and mass designations

Designation No.	**Nominal tin coating weight each surface[(a)], lb/base box**	**Minimum average coating weight each surface test value[(a)(b)], lb/base box**
Coating weights per ASTM A 624		
10	0.05/0.05	0.04/0.04
20	0.10/0.10	0.08/0.08

25	0.125/0.125	0.11/0.11
35	0.175/0.175	0.16/0.16
50	0.25/0.25	0.23/0.23
75	0.375/0.375	0.35/0.35
100	0.50/0.50	0.45/0.45
D50/25(c)	0.25/0.125	0.23/0.11
D75/25(c)	0.375/0.125	0.35/0.11
D100/25(c)	0.50/0.125	0.45/0.11
D100/50(c)	0.50/0.25	0.45/0.23
D135/25(c)	0.675/0.125	0.62/0.11

Nominal tin coating mass each surface, g/m^2	**Minimum average coating mass each surface test value(d), g/m^2**
Coating masses per ASTM A 624M	
1.1/1.1	0.9/0.9
2.2/2.2	1.8/1.8
2.8/2.8	2.5/2.5
3.9/3.9	3.6/3.6
5.6/5.6	5.2/5.2
8.4/8.4	7.8/7.8
11.2/11.2	10.1/10.1
D5.6/2.8(c)	5.2/2.5

D8.4/2.8(c)	7.8/2.5
D11.2/2.8(c)	10.1/2.5
D11.2/5.6(c)	10.1/5.2
D15.2/2.8(c)	14.0/2.5

Note: Listed above are the commonly produced coating weights and masses. Upon agreement between the producer and the purchaser, other combinations of coatings may be specified and the appropriate minimum average test values will apply.

(a) Base box is a measure of surface area equal to 31,360 in.^{2}.

(b) The minimum value shall be not less than 80% of the minimum average tin coating weight.

(c) The letter D on differentially coated tin plate indicates the coated surface to be marked. For example, the examples indicate that the heavy-coated side is marked.

(d) The minimum spot value shall be not less than 80% of the minimum average tin coating mass.

Terne Coatings

Long terne steel sheet is carbon steel sheet continuously coated by various hot dip processes with terne metal (lead with 3 to 15% tin). This coated sheet is duller in appearance than conventional tin-coated sheet, hence the name (terne) from the French, which means "dull" or "tarnished." The smooth, dull coating gives the sheet corrosion resistance, formability, excellent solderability, and paintability. The term "long terne" is used to describe terne-coated sheet, while "short terne" is used for terne-coated plate.

Because of its unusual properties, long terne sheet has been adapted to a wide variety of applications. Its greatest use is in automotive gasoline tanks. Its excellent solderability and special corrosion resistance makes the product well suited for this application.

Long terne sheet is often produced to ASTM A 308. The coatings are designated according to total coating weight on both surfaces as shown in Table 6. For applications requiring good formability, the coating is applied over low-carbon steel sheet of commercial quality, drawing quality, or drawing quality special killed, The terne coating acts as a lubricant and facilitates forming, and the strong bond of the terne metal allows it to be formed along with the basis metal. When higher strength is required, the coating can be applied over low-carbon steel sheet of structural (physical) quality, although at some sacrifice in ductility.

Phosphate Coatings

Phosphate coating of iron and steel consists of treatment with a dilute solution of phosphoric acid and other chemicals whereby the surface of the metal, reacting chemically with the phosphoric acid, is converted to an integral layer of insoluble crystalline phosphate compound. This layer is less reactive than the metal surface and at the same time is more absorbent of lubricants or paints. Because the coating is an integral part of the surface, it adheres to the basis metal tenaciously.

The chief application for iron phosphate coatings is as a paint base for nongalvanized carbon steel sheet; such a coating is usually applied on coil-coating lines. Manganese phosphate coatings are used chiefly as an oil base on engine parts for break-in and to prevent galling.

Steel Sheet for Porcelain Enameling

PORCELAIN ENAMELS are glass coatings applied primarily to products or parts made of sheet steel, cast iron, or aluminum to improve appearance and to protect the metal surface. Porcelain enamels are distinguished from other ceramic coatings on metallic substrates by their predominantly vitreous nature and the types of applications for which they are used. These coatings are differentiated from paint by their inorganic composition and coating properties. They are fused to the metallic substrate at temperatures above 425 °C (800 °F) during the firing process.

Properties of the particular steel sheet should be evaluated before its selection for enameling; some steel sheet is not recommended because of problems that complicate the process of coating the sheet with porcelain enamel. The four major problems are:

- Distortion caused by sag and warpage occurring at the temperatures reached during firing of the enamel
- Improper surface preparation that causes poor adherence
- Fishscale imperfections, particularly of the delayed variety, caused by hydrogen evolution
- Carbon boiling in the enamel coating caused by surface carbides in the steel

Steels for porcelain enameling with a single cover coat (white or colored) have since been developed. These steels, in addition to possessing single-coat coverage, have good sag resistance and freedom from carbon boiling, fishscale formation and the other problems associated with carbon, and internal imperfections. These steels are highly formable and can be drawn into more complex shapes than enameling iron.

Types of Sheet

Six types of steel sheet are available for porcelain enameling, These are described below. In most instances, a detailed review should be made with the steel supplier before ordering a particular grade or beginning production. Typical chemical analysis of the steels recommended for enameling are listed in Table 8.

Table 8 Compositions of low-carbon steels used for porcelain enameling

Type of steel	**Composition[(a)], %**								
	C	**Mn**	**P**	**S**	**Al**	**Ti**	**Nb**	**B**	**Si**
Low-carbon enameling steels[(b)]	0.02-0.04	0.15-0.3	0.015[(c)]	0.015[(c)]	0.03-0.07	. . .	. . .	0.006	0.015[(c)]
Decarburized	0.005	0.2-0.3	0.01	0.02	[(d)]	. . .	. . .	. . .	. . .
Titanium-stabilized	0.05	0.30	0.01	0.02	0.05	0.30	. . .	. . .	. . .
Interstitial-free	0.005-0.020	0.20	0.01	0.02	. . .	0.06-0.15	0.10	. . .	. . .

(a) All compositions contain balance of iron.

(b) Aluminum-killed replacement steel for enameling iron, which was a rimmed ingot-poured product formerly used for porcelain enameling.

(c) Maximum.

(d) Some steels may be supplied as aluminum-killed products.

Low-Carbon Enameling Steels (Enameling Iron Replacements). For many years, enameling iron, a rimmed-ingot poured product with a low metalloid content, was used extensively for porcelain enameling. The enameling characteristics were excellent, with the caveat that the product required a separate ground coat before applying a cover coat. Because enameling iron is a rimmed steel, it cannot be continuously cast. The movement in the steel industry to continuous casting has resulted in the recent withdrawal of the product from the market.

A number of highly serviceable enameling iron replacement products are now available for porcelain enameling. These aluminum killed steels have low carbon (0.02 to 0.04 wt%) and low manganese (0.15 to 0.30 wt%), along with 0.015 wt% P max, 0.015 wt% S max, 0.015 wt% Si max, and 0.03 to 0.07 wt% Al. Some contain a boron addition (0.006 wt% max) to aid in grain size control and to help improve resistance to enamel fishscale. The yield strength is 172 to 221 MPa (25 to 32 ksi), the tensile strength is 303 to 338 MPa (44 to 49 ksi), and the elongation is 38 to 46%.

Unlike the old enameling iron, these products do not require normalizing; they are either box annealed or continuously annealed. These processing changes result in steels that are more formable than their predecessors. Experience to date indicates that the enameling characteristics are similar to those of enameling iron, and these steels are being used in the same applications. They perform well with both ground-coat and two-coat/two-fire systems.

Decarburized Steels. The manufacture of fully decarburized sheet for direct-on cover coat enameling became practical following the development of the open coil annealing process. Different melting and teeming practices may be used to produce decarburized sheets: for instance, ladle aluminum killed-ingot poured and ladle aluminum killed-continuously cast. These aluminum killed products are not subject to the return of yield point elongation following temper rolling. As killed steels, the hot coiling off the hot strip mill eliminates the possibility of having deep drawability, but in stretch and plane strain conditions, the decarburized products are excellent performers.

Enameling characteristics for decarburized steels are excellent, and these steels are being used in all types of today's enamel systems. The low carbon content eliminates primary boiling and consequent defects such as black specks, pullthrough, and dimples caused by the evolution of carbon monoxide and carbon dioxide through the porcelain enamel coating during firing.

These steels have excellent resistance to warpage. They also exhibit good resistance to defects such as fishscale and ground-coat reboiling during firing of the cover coat, both of which are caused by the evolution of hydrogen gas. If over-pickled using the acid etch/nickel deposition metal preparation method, ladle killed steels will tend to have a "gassy" enamel surface, and enamel adherence is likely to be substandard. Ladle killing with aluminum and continuously casting is becoming the predominant way to produce these steels. It is expected that all decarburized steels will soon be manufactured by this method.

Interstitial-free steels are products in which all of the carbon and nitrogen contained in them are combined with an alloying element. Titanium or niobium (columbium), or a combination of titanium and niobium additions, are used to fully stabilize the steel. Domestically produced IF steels contain from <0.008 to 0.020 wt% C, 0.15 to 0.25 wt% Mn, 0.06 to 0.15 wt% Ti, and 0 to 0.10 wt% Nb. Vacuum degassing is used to produce the very-low-carbon versions, whereas the higher-carbon version is controlled by the basic oxygen shop.

These highly formable steels exhibit excellent strength retention after strain and firing, as well as good base metal sag properties. They do not exhibit stretcher strain and are nonaging and nonfluting. Because titanium can effect the development of ground-coat adherence, enamel systems should be optimized to ensure satisfactory adherence with these steels.

There are many specific applications in the appliance and plumbingware sector where these steels have proved to be valuable, especially where deep drawing is required. Also, these products can be produced by either ingot pouring or continuous casting, thereby ensuring their future availability.

Titanium-stabilized steels are a variation of IF steels. These steels are popular for large panels where maximum flatness can be achieved because of the product's resistance to warpage. Not being vacuum degassed, these steels are somewhat higher in carbon content than IF steels.

This carbon is stabilized as titanium carbide by the addition of titanium. Stabilization provides carbon boil resistance, a high after-fire strength, and excellent deep drawability. The higher titanium carbide content increases yield strength and reduces overall ductility. These steels offer high-temperature strength and resulting warp resistance, and they are now being produced as continuous-cast products.

Common cold-rolled steels have been used for many years in the porcelain enamel industry. They have been typically rimmed-ingot poured steels, but they are now being produced as continuous-cast products. They typically contain 0.04 to 0.07 wt% C and 0.25 to 0.040 wt% Mn. For cold-rolled drawing-quality steels, yield strength is 193 to 220 MPa (28 to 32 ksi), tensile strength is 295 to 330 MPa (43 to 48 ksi), and elongation is 40 to 44%. Enameling of cold-rolled steels should be restricted to ground coats and to noncritical appearance components.

Cold-rolled steels may also be used for two-coat enameling, where appearance is less important than in such components as range tops and other exterior parts for major appliances. Because of the high tendency of cold-rolled steel to warp and to carbon boil during porcelain enameling, the use of this material is generally restricted to components for which appreciable distortion during firing can be tolerated, applications using a low enamel firing temperature, or parts where a greater metal thickness is provided to minimize warpage. Most authorities recommend that parts fabricated from cold-rolled steels be porcelain enameled on one side only to minimize fishscale defects.

Common Hot-Rolled Steels. Hot-rolled sheets have a high susceptibility to fishscaling when porcelain enameled, especially if both sides of the steel are coated. When the use of hot-rolled steels is necessitated by the thickness/strength requirements for a given application, such as for water heater tanks, porcelain enameling should be limited to only one side of the sheet. This permits hydrogen gas, which produces the fishscaling, to escape from the unenameled side of the sheet.

Carbon and Low-Alloy Steel Plate

STEEL PLATE is any flat-rolled steel product more than 200 mm (8 in.) wide and more than 6.0 mm (0.230 in.) thick or more than 1220 mm (48 in.) wide and 4.6 mm (0.180 in.) thick. The majority of mills for rolling steel plate have a working-roll width between 2030 and 5600 mm (80 and 220 in.). Therefore, the width of product normally available ranges from 1520 to 5080 mm (60 to 200 in.). Most steel plate consumed in North America ranges in width from 2030 to 3050 mm (80 to 120 in.) and ranges in thickness from 5 to 200 mm ($\frac{3}{16}$ to 8 in.). Some plate mills, however, have the capability to roll steel more than 640 mm (25 in.) thick.

Steel plate is usually used in the hot-finished condition, but the final rolling temperature can be controlled to improve both strength and toughness. Heat treatment is also used to improve the mechanical properties of some plate.

Basic Requirements

Steel plate is mainly used in the construction of buildings, bridges, ships, railroad cars, storage tanks, pressure vessels, pipe, large machines, and other heavy structures, for which good formability, weldability, and machinability are required. The impairment of these desirable characteristics with increased carbon content usually limits the steel to the low-carbon and medium-carbon constructional grades, with the low-carbon grades predominating. Many alloy steels are also produced as plate. In the final structure, however, alloy steel plate is sometimes heat treated to achieve mechanical properties superior to those typical of the hot-finished product.

Steelmaking Practices

Killed steel is fully deoxidized, and from the viewpoint of minimum chemical segregation and uniform mechanical properties, killed steel is utilized for higher quality requirements. Therefore, killed steel is generally specified when homogeneous structure and internal soundness of the plate are required.

Vacuum degassing is used to remove dissolved oxygen and hydrogen from steel, thus reducing the number and size of indigenous nonmetallic inclusions. It also reduces the likelihood of internal fissures or "flakes" caused when hydrogen content is higher than desired.

Desulfurization. Using either hot metal desulfurization or ladle desulfurizing agents immediately before teeming (e.g., calcium or rare earth additions), final plate sulfur content can be reduced to less than 0.005%. Lower sulfur content improves plate ductility and impact properties, but adds to the cost of the steel.

Electroslag remelting is a consumable remelting process, used to produce the highest levels of quality in plate steels, particularly in thick plates. First, an ingot is melted by conventional methods, allowed to solidify in the form of an electrode, and prepared for remelting. It is then remelted through a reactive flux using a powerful electric current and again allowed to solidify. The resultant ingot is very low in sulfur and oxygen contents and free from internal blowholes and segregation.

Quality Descriptors

Steel quality, as the term applies to steel plate, is indicative of many conditions, such as degree of internal soundness, relative uniformity of mechanical properties and chemical composition, and relative freedom from injurious surface imperfections. The various types of steel plate quality are indicated in Table 9.

Table 9 Available quality levels for carbon, HSLA, and low-alloy steel plate

Carbon steel plates	HSLA steel plates	Low alloy steel plates
Regular quality	. . .	. . .
Structural quality	Structural quality	Structural quality
Drawing quality	Drawing quality	Drawing quality
Cold-drawing quality	Cold-drawing quality	Cold-drawing quality
Cold-pressing quality	. . .	. . .
Cold-flanging quality	Cold-flanging quality	Cold-flanging quality
Forging quality	Forging quality	. . .
Pressure vessel quality	Pressure vessel quality	Pressure vessel quality
. . .	. . .	Aircraft quality

Regular quality carbon steel is produced with a maximum carbon content of 0.33%. Plates of this quality are not expected to have the same degree of chemical uniformity, internal soundness, or freedom from surface imperfections associated with structural quality or pressure-vessel quality plate.

Structural quality and pressure-vessel quality steel plates usually are produced to meet specific standard specifications prepared by one of several specification-writing bodies. ASTM A 6 covers the general requirements for the structural quality steel plate products described in the individual ASTM specifications, while ASTM A 20 covers general requirements for pressure-vessel quality products.

Types of Steel

The three general categories of steel plate are carbon steel, alloy steel, and high-strength low-alloy (HSLA) steels. These three categories of steel plate are available in the steel plate quality levels given in Table 9. The various ASTM specifications for structural quality steel plate are given in Table 10. Chemical compositions of standard grades (SAE-AISI) and ASTM grades of carbon and alloy steels are given in the article "Classifications and Designations of Carbon and Alloy Steels" in this Section. Compositions, properties, and applications of HSLA steels are described in the article "High-Strength Structural and High-Strength Low-Alloy Steels." Plate steels used for elevated-temperature applications, for example, chromium-molybdenum alloy steels, are reviewed in the article "Service Characteristics of Carbon and Alloy Steels." some plate steels are also produced in more highly alloyed specialized grades, for example, high-fracture toughness steels and maraging steels. These materials are discussed in the article "Ultrahigh-Strength Steels."

Table 10 ASTM specifications for structural quality steel plate

ASTM specification[(a)]	**Steel type and condition**
Carbon steel	
A 36[(b)]	Carbon steel shapes, plates, and bars of structural quality
A 131[(c)]	Structural steel shapes, plates, bars, and rivets for use in ship construction (ordinary strength)
A 283[(b)]	Low and intermediate tensile strength carbon steel plates
A 284	Low and intermediate tensile strength carbon-silicon steel plates for machine parts and general construction
A 529[(d)]	Structural steel with 290 MPa (42 ksi) minimum yield point
A 573	Structural quality carbon-manganese-silicon steel plates with improved toughness
A 678	Quenched and tempered carbon and HSLA plates for structural applications
A 709	Carbon and HSLA steel structural shapes, plates, and bars, and quenched and tempered alloy steel for use in bridges
A 827[(e)]	Carbon steel plates for forging applications
A 830[(e)]	Structural quality carbon steel plates furnished to chemical requirements
Alloy steel	
A 514	Structural quality quenched and tempered alloy steel plates for use in welded bridges and other structures

A 709	See above under "Carbon steel"
A 710	Low-carbon age-hardening Ni-Cu-Cr-Mo-Nb, Ni-Cu-Nb, and Ni-Cu-Mn-Mo-Nb alloy steel plates, shapes, and bars for general applications
A 829(e)(f)	Structural quality alloy steel plates specified to chemical composition requirements
HSLA steel	
A 131(c)	Structural steel shapes, plates, bars, and rivets for use in ship construction (higher strength)
A 242	HSLA structural steel shapes, plates, and bars for welded, riveted, or bolted construction
A 441(g)	Mn-V HSLA steel plates, bars, and shapes
A 572	HSLA structural Nb-V steel shapes, plates, sheet piling, and bars for riveted, bolted, or welded construction of bridges, buildings, and other structures
A 588(h)	HSLA structural steel shapes, plates, and bars for welded, riveted, or bolted construction for use in bridges and buildings with atmospheric corrosion resistance approximately two times that of carbon steel with copper
A 633	Normalized HSLA structural steel for welded, riveted, or bolted construction suited for service at low ambient temperatures of -45 °C (-50 °F) or higher
A 656	Hot-rolled HSLA structural steel with improved formability for use in truck frames, brackets, crane booms, rail cars, and similar applications
A 678	See above under "Carbon steel"
A 709	See above under "Carbon steel"
A 808	Hot-rolled HSLA Mn-V-Nb structural steel plate with improved notch toughness
A 852	Quenched and tempered HSLA structural steel plate for welded, riveted, or bolted construction for use in bridges and buildings with atmospheric corrosion resistance approximately two times that of carbon steel with copper
A 871	HSLA structural steel plate in the as-rolled, normalized, or quenched and tempered condition with atmospheric corrosion resistance approximately two times that of carbon steel with copper

General requirements for structural plate are covered in ASTM A 6.

(a) Also designated with the suffix "M" when the specification covers metric equivalents.

(b) This specification is also published by the American Society of Mechanical Engineers, which uses the prefix "S" (for example, SA36).

(c) See also Section 43 of the American Bureau of Shipping specifications and MIL-S-22698 (SH).

(d) 13 mm ($\frac{1}{2}$ in.) maximum thickness.

(e) See also the AISI *Steel Products Manual.*

(f) Tensile properties may also be specified when compatible.

(g) Discontinued in 1989 and replaced by A 572.

(h) Minimum yield point 345 MPa (50 ksi) to 100 mm (4 in.). Lower minimum yield points for thicker sections

Mechanical Properties

Of the various mechanical properties normally determined for steel plate, yield strength is an important design criterion in structural applications. Tensile strength is also an important design consideration in many design codes in the United States, but is useful primarily as an indication of fatigue properties. Yield strength is a design criterion in most design codes when the ratio of yield to tensile strength is less than 0.5. Ductility, as measured by tensile elongation and reduction in area, is seldom in itself a valuable design criterion, but is sometimes used as an indication of toughness and suitability for certain applications.

The mechanical properties of steel plate in the hot-finished condition are influenced by several variables, of which chemical composition is the most influential. Other factors include deoxidation practice, finishing temperature, plate thickness, and the presence of residual elements. For steels used in the hot-finished condition (such as plate), carbon content is the single most important factor in determining mechanical properties. The static tensile properties of the various grades, types, and classes of steel plate covered by ASTM specifications are listed in Table 11. It should be noted that some of these values vary with plate thickness/width.

Table 11 ASTM mechanical property requirements for carbon and alloy steel plate

ASTM specification	Material grade or type	Tensile strength[a]		Yield strength[a]		Minimum elongation[b] in 200 mm (8 in.), %	Minimum elongation[b] in 50 mm (2 in.), %
		MPa	ksi	MPa	ksi		
Carbon steel							
A 36	. . .	400-500	58-80	220-250[b]	32-36[b]	20	23
A 131	A, B, D, E, CS, DS	400-490	58-71	220[b]	32[b]	21[b]	24
A 283	A	310-415	45-60	165	24	27	30
	B	345-405	50-65	185	27	25	28
	C	380-485	55-70	205	30	22	25
	D	415-515[b]	60-75[b]	230	33	20	23
A 284	C	415	60	205	30	21	25
	D	415	60	230	33	21	24
A 529	. . .	415-585	60-85	290	42	19	. . .
A 573	58	400-490	58-71	220	32	21	. . .
	65	450-530	65-77	240	35	20	. . .
	70	485-620	70-90	290	42	18	. . .
A 678	A	485-620	70-90	345	50	. . .	22
	B	550-690	80-100	415	60	. . .	22
	C	585-793[b]	85-115[b]	450[b]	65[b]	. . .	19
A 709	36	400-550	58-80	250	36	20	23
Alloy steel							

A 514	All	690-895(b)	100-130(b)	620(b)	90(b)	. . .	16
A 709	100, 100W	700-915	100-130	635(b)	90(b)	. . .	15(c)
A 710	A (class 1)	585(b)	85(b)	515(b)	75(b)	. . .	20
	A (class 2)	485(b)	70(b)	415(b)	60(b)	. . .	20
	A (class 3)	485(b)	70(b)	415(b)	60(b)	. . .	20
	B	605(b)	88(b)	515(b)	75(b)	. . .	18
	C (class 1)	690	100	620	90	. . .	20
	C (class 3)	620(b)	900(b)	550(b)	80(b)	. . .	20

(a) Where a single value is shown, it is a minimum.

(b) Minimum and/or maximum values depend on plate width and/or thickness.

Steel Bar, Rod, and Wire

Hot-Rolled Steel Bar and Shapes

HOT-ROLLED STEEL BARS and other hot-rolled steel shapes are produced from ingots, blooms, or billets converted from ingots, or from strand cast blooms and billets, and comprise a variety of sizes and cross sections. These bars and shapes are most often produced in straight lengths, but bars in some sizes and cross sections are also produced in coils.

The term "bar" includes: rounds, squares, hexagons, and similar cross sections 9.52 mm ($\frac{3}{8}$ in.) and greater across; flats greater than 5.16 mm (0.203 in.) in thickness and 152.4 mm (6 in.) and less in width, or 5.84 mm (0.230 in.) and greater in thickness and 203.2 mm (8 in.) and less in width; small angles, channels, tees, and other standard shapes less than 76 mm (3 in.) across; and concrete-reinforcing bars. The term "shapes" includes structural shapes and special shapes. Structural shapes are flanged, are 76 mm (3 in.) or greater in at least one cross-sectional dimension, and are used in structures such as bridges, buildings, ships, and railroad cars. Special shapes are those designed by users for specific applications.

Dimensions and Tolerances

The nominal dimensions of hot rolled steel bars and shapes are designated in inches or millimeters with applicable tolerances, as shown in ASTM specifications A 6 and A 29.

Surface Imperfections

Surface seams or laps are the most common imperfections in hot rolled bars and shapes; they appear as longitudinal fissures. Seams are crevices in the steel that have been closed, but not welded. Laps are somewhat similar imperfections that result from rolling fins or protrusions into the surface of the bar,

Allowance for Surface Imperfections. Experience has shown that when purchasers order hot-rolled or heat-treated bars that are to be machined, it is advisable for the purchaser to make adequate allowances for the removal of surface imperfections and to specify the sizes accordingly. These allowances depend on the way the surface metal is removed, the length and size of the bars, the straightness, the size tolerance, and the out-of-round tolerance. Bars are generally straightened before machining. For special quality carbon steel bars and regular quality alloy steel bars, either resulfurized or nonresulfurized, it is advisable that allowances for centerless-turned or centerless-ground bars be adequate to permit stock removal of not less than the amount shown below:

Bar diameter		Recommended minimum machining allowance per side, % of specific size	
mm	in.	Nonresulfurized	Resulfurized
≤ 51	≤ 2	2.6	3.4
>51	>2	1.6	2.4

Note that these allowances are based on bars within straightness tolerance. Also, because straightness is a function of length, additional machining allowance may be required for turning long bars on centers. For steel bars subject to magnetic particle inspection, additional stock removal is recommended, as indicated in Table 1.

Table 1 Recommended minimum stock removal for steel bars subject to magnetic particle inspection

Hot-rolled size		Minimum stock removal from the surface(a)	
mm	in.	mm	in.
Up to 12.7	Up to $\frac{1}{2}$	0.76	0.030
>12.7-19	$>\frac{1}{2}-\frac{3}{4}$	1.14	0.045
>19-25	$>\frac{3}{4}-1$	1.52	0.060
>25-38	$>1-1\frac{1}{2}$	1.90	0.075

>38-51	>$1\frac{1}{2}$-2	2.29	0.090
>51-64	>2-$2\frac{1}{2}$	3.18	0.125
>64-89	>$2\frac{1}{2}$-$3\frac{1}{2}$	3.96	0.156
>89-114	>$3\frac{1}{2}$-$4\frac{1}{2}$	4.75	0.187
>114-152	>$4\frac{1}{2}$-6	6.35	0.250
>152-191	>6-$7\frac{1}{2}$	7.92	0.312
>191-229	>$7\frac{1}{2}$-9	9.52	0.375
>229-254	>9-10	11.10	0.437

(a) The minimum reduction in diameter of rounds is twice the minimum stock removal from the surface.

Product Requirements

Hot-rolled steel bars and shapes can be produced to chemical composition ranges or limits, mechanical property requirements, or both. The mechanical testing of hot-rolled steel bars and shapes can include tensile, Brinell or Rockwell hardness, bend, Charpy impact, fracture toughness, and short-time elevated-temperature tests, as well as tests for elastic limit, proportional limit, and offset yield strength, which require the use of an extensometer or plotting of a stress-strain curve. These tests are covered by ASTM A 370 and other ASTM standards.

Other tests sometimes required include the measurement of grain size and hardenability. Austenitic grain size is determined by the McQuaid-Ehn test, which is described in ASTM E 112. This test involves metallographic examination of a carburized specimen to observe prior austenitic grain boundaries. Hardenability can be measured by several methods, the most common being the Jominy end-quench test, as described in ASTM A 255 (see the article "Hardenability of Carbon and Alloy Steels" in this Section).

Soundness and homogeneity can be evaluated by fracturing. The fracture test is commonly applied only to high-carbon bearing quality steel. Location of samples, number of tests, details of testing technique, and acceptance limits based on the test should be established in each instance.

Testing for nonmetallic inclusions consists of careful microscopic examination (at 100×) of prepared and polished specimens. The specimens should be taken on a longitudinal plane midway between the center and surface of the product. Location of specimens, number of tests, and interpretation of results should be established in each instance. Typical testing procedures are described in ASTM E 45.

Tensile and hardness tests are the most common mechanical tests performed on hot-rolled steel bars and shapes. Hardness is a relatively simple property to measure, and it is closely related to tensile strength, as shown in Fig. 1. When Fig. 2 is used together with Fig. 1, a simple hardness test can give an estimate of yield strength and elongation, as well as tensile strength.

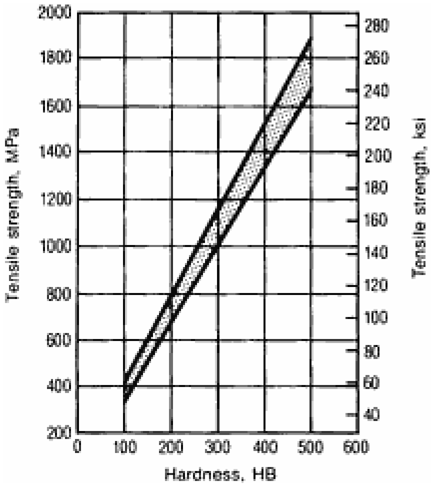


Fig. 1 Relationship between hardness and tensile strength of steel. Range up to 300 HB is applicable to the hot-finished steel discussed in this article.

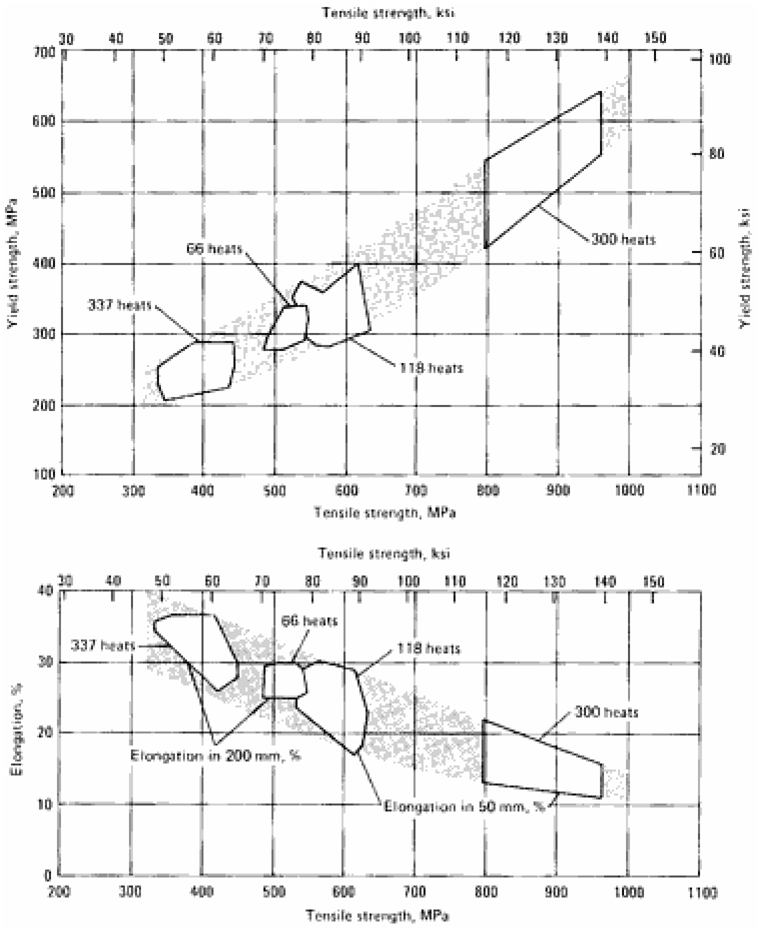


Fig. 2 Relation of tensile properties for hot-rolled carbon steel

It is not practicable to set definite limitations on tensile strength or hardness for carbon or alloy steel bars in the as-rolled condition. For mill-annealed steel bars, there is a maximum tensile strength or a maximum hardness (Table 2) that can be expected for each grade of steel. For steel bars in the normalized condition, maximum hardness, maximum tensile strength, minimum hardness, or minimum tensile strength can be specified. For normalized and tempered bars and for quenched and tempered bars, either maximum and minimum hardness or maximum and minimum tensile strength can be specified; for either property, the range that can be specified varies with tensile strength and is equivalent to a 0.4 mm range of Brinell indentation diameters at any specified location for normalized and tempered bars and to a 0.3 mm range for quenched and tempered bars.

Table 2 Lowest maximum hardness that can be expected for hot-rolled steel bars, billets, and slabs with ordinary mill annealing

Steel grade	**Maximum hardness**[(a)], **HB**	
	Straightened	**Non-straightened**
Carbon steels		
1141	201	192
1144	207	197
1151	207	201
1541	207	197
1548	212	207
1552	212	207
15B41	207	197
15B48	212	207
Alloy steels		
1330	187	179
1335	197	187
1340	201	192
1345	212	201
4012	149	143
4023	156	149

4024	156	149
4027	170	163
4028	170	163
4037	192	183
4047	212	201
4118	170	163
4130	183	174
4137	201	192
4140	207	197
4142	212	201
4145	217	207
4147	223	212
4150	235	223
4161	241	229
4320	207	197
4340	235	223
4419	170	163
4615	174	167
4620	179	170
4621	179	170
4626	187	179

4718	179	170
4720	170	163
4815	223	192
4817	229	197
4820	229	197
5015	156	149
50B44	207	197
50B46	217	201
50B50	217	201
50B60	229	217
5120	170	163
5130	183	174
5132	187	179
5135	192	183
5140	197	187
5145	229	197
5147	217	207
5150	212	201
5155	229	217
5160	235	223
51B60	235	223

6118	163	156
6150	217	207
81B45	201	192
8615	163	156
8617	163	156
8620	170	163
8622	179	170
8625	179	170
8627	183	174
8630	187	179
8637	201	192
8640	207	197
8642	212	201
8645	217	207
8655	235	223
8720	170	163
8740	212	201
8822	187	179
9254	241	229
9255	241	229
9260	248	235

94B17	156	149
94B30	183	174

(a) Specific microstructure requirements may necessitate modification of these hardness numbers.

Product Categories

Hot-rolled carbon steel bars are produced to two primary quality levels: merchant quality and special quality. Merchant quality is the lower quality level and is not suitable for any operation in which internal soundness or freedom from surface imperfections is of primary importance. Special quality includes all bar categories with end-use-related and restrictive quality requirements.

Merchant Quality Bars

Merchant quality is the least restrictive descriptor for hot-rolled carbon steel bars. Merchant quality bars are used in the production of noncritical parts of bridges, buildings, ships, agricultural implements, road-building equipment, railway equipment, and general machinery. These applications require only mild cold bending, mild hot forming, punching, and welding. Mild cold bending is bending in which a generous bend radius is used and in which the axis of the bend is at right angles to the direction of rolling.

Grades. Merchant quality bars can be produced to meet both chemical composition (heat analysis only) and mechanical properties. These steels can be supplied to chemical compositions within the ranges of 0.50% C (max), 0.60% Mn (max), 0.04% P (max), and 0.05% S (max),but are not produced to meet any specific silicon content, grain size, or any other requirement that would dictate the type of steel produced.

Merchant quality steel bars do not require the chemical ranges typical of standard steels. They are produced to wider carbon and manganese ranges and are designated by the prefix "M."

Mechanical Properties. When ordering merchant quality bars to meet mechanical properties, the following strength ranges are to be used up to a maximum of 655 MPa (95 ksi):

- 70 MPa (10 ksi) for minimums up to but not including 415 MPa (60 ksi)
- 80 MPa (12 ksi) for minimums from 415 MPa (60 ksi) up to but not including 460 MPa (67 ksi)
- 100 MPa (15 ksi) for minimums from 460 to 550 MPa (67 to 80 ksi)

Specification ASTM A 663 defines the requirements for hot-wrought merchant quality carbon steel bars and bar-size shapes intended for noncritical constructional applications.

Sizes. Merchant quality steel rounds are not produced in diameters greater than 76 mm (3 in.).

Special Quality Bars

Special quality steel bars are employed when end use, method of fabrication, or subsequent processing treatment requires characteristics not available in merchant quality bars. Typical applications, including many structural uses, require hot forging, heat treating, cold drawing, cold forming and machining.

Special quality bars are required to be free from visible pipe and excessive chemical segregation. Also, they are rolled from blooms and billets that have been inspected and conditioned, as necessary, to minimize surface imperfections.

Table 3 Typical ASTM specifications for structural quality steel bars and steel structural shapes. Covered in ASTM A6

Specification	Steel type and condition
Carbon Steels	
A 36[(a)(b)]	Carbon steel plates, bars, and shapes
A 131[(c)]	Carbon and HSLA steel plates, bars, shapes, and rivets for ships
A 529	Carbon steel plates, bars, shapes, and sheet piling with minimum yield strength of 290 MPa (42 ksi)
A 709	Carbon, alloy, and HSLA steel plates, bars, and shapes for bridges
Alloy steel	
A 710	Age-hardening low-carbon Ni-Cu-Cr-Mo-Nb and Ni-Cu-Nb alloy steel plates, bars, and shapes
High-strength low-alloy (HSLA) steels	
A 131[(c)]	See above under "Carbon steels"
A 242	HSLA steel plates, bars, and shapes
A 572	Nb-V HSLA steel plates, bars, shapes, and sheet piling
A 588	HSLA steel plates, bars, and shapes with minimum yield point of 345 MPa (50 ksi)
A 633	Normalized HSLA steel plates, bars, and shapes
A 690	HSLA steel H-piles and sheet piling for use in marine environments

(a) This ASTM specification is also published by the American Society of Mechanical Engineers, which adds an S in front of the A.

(b) See also Canadian Standards Association (CSA) specification G40.8.

(c) See also Section 39 of the ABS specifications.

Mechanical Properties. Some special quality steel bars are produced to specified mechanical properties, Tensile properties are identical to those of the merchant quality bars described above.

Sizes. Special quality steel bars are commonly produced in the following sizes:

- *Rounds:* 6.4 to 254 mm ($\frac{1}{4}$ to 10 in.)
- *Squares:* 6.4 to 154 mm ($\frac{1}{4}$ to 6$\frac{1}{16}$ in.)
- *Round-cornered squares:* 9.5 to 203 mm ($\frac{3}{8}$ to 8 in.)
- *Hexagons:* 9.5 to 103 mm ($\frac{3}{8}$ to 4$\frac{1}{16}$ in.)
- *Flats:* greater than 5.16 mm (0.203 in.) in thickness and 152 mm (6 in.) and less in width, or 5.84 mm (0.230 in.) and greater in thickness and 203 mm (8 in.) and less in width

Alloy Steel Bars

Hot-rolled alloy steel bars are commonly produced in the same size ranges as special quality steel bars. Both hot-rolled alloy and high-strength low-alloy steel bars are covered by ASTM specifications (Tables 3, 4). Many of the alloys covered in these specifications are standard SAE-AISI grades. Hot-rolled alloy steel bars are also produced for bearing applications and aircraft parts. Bearing-quality steels are described in the article "Bearing Steels" in this Section. Aircraft quality grades are often made to Aerospace Material Specifications (AMS).

Table 4 Typical ASTM specification for hot-rolled steel bars

Specification	**Steel type and condition**
Carbon steels	
A 321[(a)]	Quenched and tempered carbon steel bars
A 575[(a)]	Merchant quality carbon steel bars
A 576[(a)]	Special quality carbon steel bars
A 663[(a)]	Merchant quality carbon steel bars subject to mechanical property requirements
A 675[(a)]	Special quality carbon steel bars subject to mechanical property requirements
Alloy steels	
A 295	Bearing quality high-carbon chromium steel billets, forgings, tube rounds, bars, rods, and tubes
A 304[(a)]	Alloy steel bars subject to end-quench hardenability requirements
A 322[(a)]	Alloy steel bars for regular constructional applications
A 434[(a)]	Quenched and tempered alloy steel bars, hot rolled or cold finished
A 485	Bearing quality high-carbon chromium steel billets, tube rounds, bars, and tubes modified for high hardenability

A 534	Carburizing alloy steel billets, tube rounds, bars, rods, wire, and tubes of bearing quality
A 535	Special quality alloy steel billets, bars, tube rounds, rods, and tubes for the manufacture of antifriction bearings

See Table 3 for ASTM specifications for structural quality bars and structural shapes.

(a) Covered in ASTM A 29

Cold-Finished Steel Bars

COLD-FINISHED STEEL BARS are carbon and alloy steel bar products (round, square, hexagonal, flat, or special shapes) that are produced by cold finishing previous hot-wrought bars by means of cold drawing, cold forming, turning, grinding, or polishing (singly or in combination) to yield straight lengths or coils that are uniform throughout their length. Not covered here are flat-rolled products such as sheet, strip, or plate, which are normally cold finished by cold rolling, or cold-drawn tubular products.

Cold-finished bars fall into five classifications: cold-drawn bars; turned and polished (after cold draw or hot roll) bars; cold-drawn, ground, and polished (after cold draw) bars; turned, ground, and polished bars; and cold-drawn, turned, ground, and polished bars.

Cold-drawn bars represent the largest tonnage production and are widely used in the mass production of machined and other parts. They have attractive combinations of mechanical and dimensional properties.

Turned and polished bars have the mechanical properties of hot-rolled products but have greatly improved surface finish and dimensional accuracy. These bars are available in sizes larger than those that can be cold drawn. Turned bars are defect and decarb free.

Cold-drawn, ground, and polished bars have the increased machinability, tensile strength, and yield strength of cold-drawn bars together with very close size tolerances. However, cold-drawn, ground, and polished bars are not guaranteed to be defect free.

Turned, ground, and polished bars have superior surface finish, dimensional accuracy, and straightness. These bars find application in precision shafting and in plating, where such factors are of primary importance.

Cold-drawn, turned, ground, and polished bars have improved mechanical properties, close size tolerances, and a surface free of imperfections.

Bar Sizes

Cold-finished steel bars are available in a wide variety of sizes and cross-sectional shapes. Normally, they are furnished in straight lengths, but in some sizes and cross sections they may be furnished in coils. Cold-finished steel bars are available with nominal dimensions designated in either inches or millimeters. Cold-finished product is available in standard size increments, which vary by size range. Special sizes can be negotiated depending on hot mill increments and cold-finish tooling. The sizes in which they are commonly available in bar form are given in Table 5.

Table 5 Commercially available sizes of cold-finished steel bars

Configuration	Minimum thickness or diameter		Maximum thickness or diameter		Size increments		Normal length	
	mm	in.	mm	in.	mm	in.	m	ft
Round	3.2	0.125	305	12	0.8-25	32nds to 1 in.	3.0-3.7 or 6.1-7.3	10-12 or 20-24
					1.6-75	16ths to 3 in.		
					3.2-152	8ths to 6 in.		
Square	3.2	0.125	152	6	1.6-38	16ths to $1\frac{1}{2}$ in.	3.0-3.7	10-12
					3.2-70	8ths to $2\frac{3}{4}$ in.		
Hexagonal	3.2	0.125	102	4	1.6-50	16ths to 2 in.	3.0-3.7	10-12
					6.4-102	4ths to 4 in.		
Flat	3.2 thick × 6.4 wide	0.125 thick × 0.25 wide	76 × 371	3 thick × $14\frac{5}{8}$ wide	1.6-17	16ths to $\frac{11}{16}$ in.	3.0-3.7	10-12
					3.2-44	8ths to $1\frac{3}{4}$ in.		

Product Types

In the manufacture of cold-finished bars, the steel is first hot rolled oversize to appropriate shape and is then subjected to mechanical operations (other than those intended primarily for scale removal) that affect its machinability, straightness, and end-cut properties. As indicated above, the two common methods of cold finishing bars are (a) removal of surface material by turning or grinding, singly or in combination, and (b) drawing the material through a die of suitable configuration.

Commercial Grades. Any grade of carbon or alloy steel that can be hot rolled can also be cold finished. The choice of grade is based on the attainable cold-finished and/or hardenability and tempering characteristics necessary to obtain the required mechanical properties.

Cold drawn carbon steels are most common in grades with less than 0.55% carbon. Grades above this carbon level must be annealed before cold drawing, which increases cost, and their ultimate mechanical properties after annealing and cold drawing may be lower than those of lower-carbon grades cold drawn directly from hot rolled stock. Some improvement in machining characteristics of the higher-carbon grades can be obtained by annealing.

Alloy steels containing more than 0.38% carbon must be annealed before cold drawing.

Machined Bars. Bar products that are cold finished by stock removal can be: turned and polished; turned, ground, and polished; cold drawn, ground and polished; cold drawn, turned and polished; and cold drawn, turned, ground, and polished. Turning is done in special machines with cutting tools mounted in rotating heads, thus eliminating the problem of having to support long bars as in a lathe. Grinding is done in centerless machines. Polishing can be done in a roll straightener of the crossed-axis (Medart) type with polished rolls to provide a smooth finish. Polishing by grinding with an organic wheel or with a belt is also employed.

The published range of diameters both for turned and for turned and ground bars is 13 to 229 mm ($\frac{1}{2}$ to 9 in.) inclusive; for cold-drawn and ground bars, it is 3.2 to 102 mm ($\frac{1}{8}$ to 4 in.) inclusive. These are composites of size ranges throughout the industry; an individual producer may be unable to furnish a full range of sizes. For example, one well-known producer supplies turned rounds from 13 to 229 mm ($\frac{1}{2}$ to 9 in.), another from 29 to 203 mm ($1\frac{1}{8}$ to 8 in.)--all finished sizes.

Stock removal in turning, or turning and grinding, measured on the diameter, is normally 1.6 mm ($\frac{1}{16}$ in.) for sizes up to 38 mm ($1\frac{1}{2}$ in.), 3.2 mm ($\frac{1}{8}$ in.) for the 38 to 76 mm ($1\frac{1}{2}$ to 3 in.) range, 4.8 mm ($\frac{3}{16}$ in.) for the 76 to 127 mm (3 to 5 in.) range, and 6.4 mm ($\frac{1}{4}$ in.) for 127 mm (5 in.) diameter and larger.

Cold-drawn round bars are available in a range of diameters from 3.2 to 152 mm ($\frac{1}{8}$ to 6 in.). The maximum diameters available from individual producers, however, may vary from 76 to 152 mm (3 to 6 in.). The reduction in diameter in cold drawing, called draft, is commonly 0.79 mm ($\frac{1}{32}$ in.) for finished sizes up to 9.5 mm ($\frac{3}{8}$ in.) and 1.6 mm ($\frac{1}{16}$ in.) for sizes over 9.5 mm ($\frac{3}{8}$ in.). Some special processes use heavier drafts followed by stress relieving. One producer employs heavy drafting at elevated temperature. With this exception, drawing operations are begun with the material at room temperature, and the only elevated temperature involved is that developed in the bar as a result of drawing; this temperature rise is small and of little significance.

Originally, cold finishing, whether by turning or by cold rolling, was employed only for sizing to produce a bar with closer dimensional tolerances and a smoother surface. As cold-finished bar products were developed and improved, increased attention was paid to the substantial enhancement of mechanical properties that could be obtained by cold working. This additional advantage is now more fully appreciated, as evidenced by the fact that increased mechanical properties are an important consideration in about 40% of the applications. In approximately half of these applications, or 20% of the total, cold drawing is used only to increase strength; in the other 20%, close tolerances and better surface finish are desired in addition to increased strength.

As-rolled microalloyed high-strength low-alloy (HSLA) steels or microalloyed HSLA steels in various combinations of controlled drafting and furnace treatment provide an extension of property attainment. A high percentage of free-machining steels are cold drawn for the combination of size accuracy and improved machinability. Recent developments in microalloyed steels provide hot-rolled turned bars, under certain circumstances, having mechanical properties similar to cold-drawn nonmicroalloyed steels.

Turning Versus Cold Drawing. Basic differences exist between bars finished by turning and those finished by cold drawing. First, it is obvious that turning and centerless grinding are applicable only to round bars, while drawing can be applied to a variety of shapes. Drawing, therefore, is more versatile than turning.

Second, there is a difference in the number and severity of the surface imperfections that may be present. Because stock is removed in turning and grinding, shallow surface imperfections and decarburization may be completely eliminated. When material is drawn, stock is only displaced, and surface imperfections are only reduced in depth.

Different size tolerances are applicable to cold-finished products, depending on shape, carbon content and heat treatment. Listed in Tables 6, 7, and 8 are the tolerances for cold-finished carbon and alloy steel bars published in ASTM A 29. These tables include cold-drawn bars; turned and polished rounds; cold-drawn, ground, and polished rounds; and turned, ground, and polished rounds. From the data in Tables 6, 7, and 8, certain generalizations can be stated. The tolerances for cold-drawn and for turned and polished rounds, for example, are the same for sizes up to and including 102 mm (4 in.). There are differences, however, between the tolerances that apply to carbon steel and those that apply to alloy steels. Tolerances for several finishes also vary with certain levels of carbon content. Broader tolerances are applicable to bars that have been heat treated before cold finishing. In contrast, tolerances are closer when bars are ground, and these tolerances are independent of carbon content.

Table 6 Size tolerances for cold-finished carbon steel bars, cold drawn or turned and polished

Size		**Size tolerance**									
		Maximum carbon (C) range, %								**All grades quenched and tempered or normalized before cold finishing**	
		C $\leq$0.28		**0.28 < C $\leq$ 0.55**		**C $\leq$0.55 including stress relief or annealed after cold finishing**		**C > 0.55**			
mm	**in.**	**mm**	**in.**	**mm**	**in.**	**mm**	**in.**	**mm**	**in.**	**mm**	**in.**
Rounds--cold drawn (to 102 mm, or 4 in., in size) or turned and polished											
To 38 inclusive	To $1\frac{1}{2}$ inclusive	-0.05	-0.002	-0.08	-0.003	-0.10	-0.004	-0.13	-0.005	-0.13	-0.005
>38-64 inclusive	>$1\frac{1}{2}$-$2\frac{1}{2}$ inclusive	-0.08	-0.003	-0.10	-0.004	-0.13	-0.005	-0.15	-0.006	-0.15	-0.006
>64-102 inclusive	>$2\frac{1}{2}$-4 inclusive	-0.10	-0.004	-0.13	-0.005	-0.15	-0.006	-0.18	-0.007	-0.18	-0.007
>102-152 inclusive	>4-6 inclusive	-0.13	-0.005	-0.15	-0.006	-0.18	-0.007	-0.20	-0.008	-0.20	-0.008
>152-203 inclusive	>6-8 inclusive	-0.15	-0.006	-0.18	-0.007	-0.20	-0.008	-0.23	-0.009	-0.23	-0.009
>203-229 inclusive	>8-9 inclusive	-0.18	-0.007	-0.20	-0.008	-0.23	-0.009	-0.25	-0.010	-0.25	-0.010

Hexagons--cold drawn											
To 19 inclusive	To $\frac{3}{4}$ inclusive	-0.05	-0.002	-0.08	-0.003	-0.10	-0.004	-0.15	-0.006	-0.15	-0.006
>19-38 inclusive	>$\frac{3}{4}$-1$\frac{1}{2}$ inclusive	-0.08	-0.003	-0.10	-0.004	-0.13	-0.005	-0.18	-0.007	-0.18	-0.007
>38-64 inclusive	>1$\frac{1}{2}$-2$\frac{1}{2}$ inclusive	-0.10	-0.004	-0.13	-0.005	-0.15	-0.006	-0.20	-0.008	-0.20	-0.008
>64-80 inclusive	>2$\frac{1}{2}$-3$\frac{1}{8}$ inclusive	-0.13	-0.005	-0.15	-0.006	-0.18	-0.007	-0.23	-0.009	-0.23	-0.009
>80-102 inclusive	>3$\frac{1}{8}$-4 inclusive	-0.13	-0.005	-0.15	-0.006	. . .	. . .	. . .	. . .	. . .	. . .
Squares--cold drawn(a)											
To 19 inclusive	To $\frac{3}{4}$ inclusive	-0.05	-0.002	-0.10	-0.004	-0.13	-0.005	-0.18	-0.007	-0.18	-0.007
>19-38 inclusive	>$\frac{3}{4}$-1$\frac{1}{2}$ inclusive	-0.08	-0.003	-0.13	-0.005	-0.15	-0.006	-0.20	-0.008	-0.20	-0.008
>38-64 inclusive	>1$\frac{1}{2}$-2$\frac{1}{2}$ inclusive	-0.10	-0.004	-0.15	-0.006	-0.18	-0.007	-0.23	-0.009	-0.23	-0.009
>64-102 inclusive	>2$\frac{1}{2}$-4 inclusive	-0.15	-0.006	-0.20	-0.008	-0.23	-0.009	-0.28	-0.011	-0.28	-0.011
>102-127 inclusive	>4-5 inclusive	-0.25	-0.010	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
>127-152 inclusive	>5-6 inclusive	-0.36	-0.014	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Flats--cold drawn(a)(b)											
To 19 inclusive	To $\frac{3}{4}$ inclusive	-0.08	-0.003	-0.10	-0.004	-0.15	-0.006	-0.20	-0.008	-0.20	-0.008

>19-38 inclusive	$>\frac{3}{4}$-1$\frac{1}{2}$ inclusive	-0.10	-0.004	-0.13	-0.005	-0.20	-0.008	-0.25	-0.010	-0.25	-0.010
>38-75 inclusive	>1$\frac{1}{2}$-3 inclusive	-0.13	-0.005	-0.15	-0.006	-0.25	-0.010	-0.30	-0.012	-0.30	-0.012
>75-102 inclusive	>3-4 inclusive	-0.15	-0.006	-0.20	-0.008	-0.28	-0.011	-0.40	-0.016	-0.40	-0.016
>102-152 inclusive	>4-6 inclusive	-0.20	-0.008	-0.25	-0.010	-0.30	-0.012	-0.50	-0.020	-0.50	-0.020
>152	>6	-0.33	-0.013	-0.38	-0.015	. . .	. . .	. . .	. . .	. . .	. . .

This table includes tolerances for bars that have been annealed, spheroidize annealed, normalized, normalized and tempered, or quenched and tempered before cold finishing. This table does not include tolerances for bars that are annealed, spheroidize annealed, normalized, normalized and tempered, or quenched and tempered after cold finishing; the producer should be consulted for tolerances for such bars.

(a) Tolerances can be ordered all plus, or distributed plus and minus with the sum equivalent to the tolerances listed.

(b) Width governs the tolerance for both width and thickness of flats, for example, when the maximum of carbon range is 0.28% or less for a flat 50 mm (2 in.) wide and 25 mm (1 in.) thick. The width tolerance is 0.13 mm (0.005 in.), and the thickness is the same, nearly 0.13 mm (0.005 in.).

Table 7 Size tolerances for cold-finished alloy steel bars, cold drawn or turned and polished

Size		**Size tolerance**									
		Maximum carbon (C) range, %								**All carbon quenched and tempered (heat treated) or normalized and tempered before cold finishing**	
		C ≤ 0.28		**0.28 > C ≤ 0.55**		**C ≤ 0.55 including stress relief or annealed after cold finishing**		**C > 0.55 with or without stress relieving or annealing after cold finishing**			
mm	**in.**	**mm**	**in.**	**mm**	**in.**	**mm**	**in.**	**mm**	**in.**	**mm**	**in.**
Rounds--cold drawn (to 102 mm, or 4 in., in size) or turned and polished											
In coils: To 25 inclusive	To 1 inclusive	0.05	0.002	0.08	0.003	0.10	0.004	0.13	0.005	0.13	0.005
Cut lengths: To 38 inclusive	To 1 $\frac{1}{2}$	0.08	0.003	0.10	0.004	0.13	0.005	0.15	0.006	0.15	0.006

	inclusive										
>38-64 inclusive	>1 $\frac{1}{2}$ -2 $\frac{1}{2}$ inclusive	0.10	0.004	0.13	0.005	0.15	0.006	0.18	0.007	0.18	0.007
>64-102 inclusive	>2 $\frac{1}{2}$ -4 inclusive	0.13	0.005	0.15	0.006	0.18	0.007	0.20	0.008	0.20	0.008
>102-152 inclusive	>4-6 inclusive	0.15	0.006	0.18	0.007	0.20	0.008	0.23	0.009	0.23	0.009
>152-203 inclusive	>6-8 inclusive	0.18	0.007	0.20	0.008	0.23	0.009	0.25	0.010	0.25	0.010
>203-229 inclusive	>8-9 inclusive	0.20	0.008	0.23	0.009	0.25	0.010	0.28	0.011	0.28	0.011
Hexagon--cold drawn											
To 19 inclusive	To $\frac{3}{4}$ inclusive	0.08	0.003	0.10	0.004	0.13	0.005	0.18	0.007	0.18	0.007
>19-38 inclusive	> $\frac{3}{4}$ -1 $\frac{1}{2}$ inclusive	0.10	0.004	0.13	0.005	0.15	0.006	0.20	0.008	0.20	0.008
>38-64 inclusive	>1 $\frac{1}{2}$ -2 $\frac{1}{2}$ inclusive	0.13	0.005	0.15	0.006	0.18	0.007	0.23	0.009	0.23	0.009
>64-79 inclusive	>2 $\frac{1}{2}$ -3 $\frac{1}{8}$ inclusive	0.15	0.006	0.18	0.007	0.20	0.008	0.25	0.010	0.25	0.010
>79-102 inclusive	>3 $\frac{1}{8}$ -4 inclusive	0.15	0.006	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Squares--cold drawn											
To 19 inclusive	To $\frac{3}{4}$ inclusive	0.08	0.003	0.13	0.005	0.15	0.006	0.20	0.008	0.20	0.008

>19-38 inclusive	$>\frac{3}{4}$-1 $\frac{1}{2}$ inclusive	0.10	0.004	0.15	0.006	0.18	0.007	0.23	0.009	0.23	0.009
>38-64 inclusive	>1 $\frac{1}{2}$-2 $\frac{1}{2}$ inclusive	0.13	0.005	0.18	0.007	0.20	0.008	0.25	0.010	0.25	0.010
>64-102 inclusive	>2 $\frac{1}{2}$-4 inclusive	0.18	0.007	0.23	0.009	0.25	0.010	0.30	0.012	0.30	0.012
>102-127 inclusive	>4-5 inclusive	0.28	0.011	0.23	. . .	0.25	. . .	0.30	. . .	0.30	. . .
Flats--cold drawn[(a)]											
To 19 inclusive	To $\frac{3}{4}$ inclusive	0.10	0.004	0.13	0.005	0.18	0.007	0.23	0.009	0.23	0.009
>19-38 inclusive	$>\frac{3}{4}$-1 $\frac{1}{2}$ inclusive	0.13	0.005	0.15	0.006	0.23	0.009	0.28	0.011	0.28	0.011
>38-76 inclusive	>1 $\frac{1}{2}$-3 inclusive	0.15	0.006	0.18	0.007	0.28	0.011	0.33	0.013	0.33	0.013
>76-102 inclusive	>3-4 inclusive	0.18	0.007	0.23	0.009	0.30	0.012	0.43	0.017	0.43	0.017
>102-152 inclusive	>4-6 inclusive	0.23	0.009	0.28	0.011	0.33	0.013	0.52	0.021	0.52	0.021
>152	>6	0.36	0.014	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

This table includes tolerances for bars that have been annealed, spheroidize annealed, normalized, normalized and tempered, or quenched and tempered before cold finishing. This table does not include tolerances for bars that are annealed, spheroidize annealed, normalized, normalized and tempered, or quenched and tempered after cold finishing; the producer should be consulted for tolerances for such bars.

(a) Width governs the tolerance for both width and thickness of flats, for example, when the maximum of carbon range is 0.28% or less for a flat 50 mm (2 in.) wide and 25 mm (1 in.) thick. The width tolerance is 0.13 mm (0.005 in.), and the thickness is the same, nearly 0.13 mm (0.005 in.).

Table 8 Size tolerances for cold-finished carbon and alloy steel round bars cold drawn, ground, and polished or turned, ground, and polished

Size				Tolerances from specified size	
Cold drawn, ground, and polished		Turned, ground, and polished			
mm	in.	mm	in.	mm	in.
To 38 incl	to $1\frac{1}{2}$ incl	To 38 incl	To $1\frac{1}{2}$ incl	-0.03	-0.001
>38-64 incl	>$1\frac{1}{2}$ -$2\frac{1}{2}$ excl	>38-64 incl	>$1\frac{1}{2}$ -$2\frac{1}{2}$ excl	-0.04	0.0015
>64-76 incl	$\geq 2\frac{1}{2}$ -3 incl	>64-76 incl	$\geq 2\frac{1}{2}$ -3 incl	-0.05	-0.002
>76-102 incl	>3-4 incl	>76-102 incl	>3-4 incl	-0.08	-0.003
. . .	. . .	>102-152 incl	>4-6 incl	-0.10[(a)]	-0.004[(a)]
. . .	. . .	>152	>6	-0.13[(a)]	-0.005[(a)]

Incl, inclusive; excl, exclusive.

(a) For nonresulfurized steels (steels specified to maximum sulfur limits under 0.08%) or for steels thermally treated, the tolerance is increased by 0.03 mm (0.001 in.).

Carbon Steel Quality Descriptors

Standard quality is the descriptor applied to the basic quality level to which cold-finished carbon steel bars are produced. Standard quality cold-finished bars are produced from hot-rolled carbon steel of special quality (the standard quality for hot-rolled bars for cold finishing). Steel bars of standard quality must be free from visible pipe and excessive chemical segregation. They may contain surface imperfections. In general, the size of surface imperfections increases with bar size.

Restrictive requirement quality A (RRA) incorporates all the features of standard quality carbon steel bars described above, plus any one of the following restrictive requirements.

Special surface bars are produced with special surface preparation to minimize the frequency and size of seams and other surface imperfections. These bars are used for applications in which machining allowances do not allow sufficient surface removal to clean up the detrimental imperfections that occur in standard quality bars.

Special internal soundness bars have greater freedom from chemical segregation and porosity than standard quality bars

Special hardenability bars are produced to hardenability requirements other than those of standard H-steels.

Cold-finished carbon steel bars are also produced to inclusion ratings as determined by standard nonmetallic inclusion testing.

Restrictive requirement quality B (RRB) incorporates all the features of standard quality carbon steel bars, plus any one of the following.

Special discard is specified when minimized chemical segregation, special steel cleanliness, or internal soundness requirements dictate that the product be selected from certain positions in the ingot.

Minimized decarburization is specified whenever decarburization is important, as in heat treating for surface hardness requirements.

Single restrictions other than those noted above, such as special chemical limitations, special processing techniques, and other special characteristics not previously anticipated are also covered by this quality level.

Multiple restrictive requirement quality (MRR) applies when two or more of the above-described restrictive requirements are involved.

Cold-forging quality A and cold-extrusion quality A apply to cold-finished carbon steel bars used in the production of solid or hollow shapes by means of cold plastic deformation involving the movement of metal by compression with no expansion of the surface and not requiring special inspection standards.

Cold-heading quality, cold-extrusion quality B, cold-upsetting quality, and cold-expansion quality apply to cold-finished carbon steel bars used in production of solid or hollow shapes by means of severe cold plastic deformation by cold heading, cold extrusion, cold upsetting, or cold expansion involving movement of metal by expansion and/or compression. Such bars are obtained from steel produced by closely controlled steelmaking practices and are subject to special inspection standards for internal soundness and surface quality and uniform chemical composition. For grades of steel with a maximum specified carbon content of 0.30% or more, an anneal or spheroidize anneal heat treatment may be required to obtain the proper hardness and microstructure for cold working.

Restrictive cold-working quality applies to cold-finished carbon steel bars used in the production of solid or hollow shapes by means of very severe cold plastic deformation involving cold working by expansion and/or compression.

Other Carbon Steel Qualities. The quality descriptors listed below are some of those that apply to cold-finished carbon steel bars intended for specific requirements and applications. They may have requirements for surface quality, amount of discard, macroetch tests, mechanical properties, or chemical uniformity as indicated in product specifications:

- Axle shaft quality
- Shell steel quality A
- Shell steel quality C
- Rifle barrel quality
- Spark plug quality

Alloy Steel Quality Descriptors

Regular quality is the descriptor applied to the basic, or standard, quality level to which cold-finished alloy steel bars are produced. Steels for this quality are killed and are usually produced to a fine grain size. They are melted to chemical ranges and limits and are inspected and tested to meet normal requirements for regular constructional alloy steel applications. Regular quality cold-finished alloy steel bars may contain surface imperfections. In general, the size of detrimental surface imperfections increases with bar size.

Cold-heading quality applies to cold-finished alloy steel bars intended for applications involving cold plastic deformation by such operations as upsetting, heading, or forging. Bars are supplied from steel produced by closely controlled steelmaking practices and are subject to mill testing and inspection designed to ensure internal soundness, uniformity of chemical composition, and freedom from detrimental surface imperfections. Proper control of hardness and microstructure by heat treatment and cold working is important for cold forming. Most cold-heading quality alloy steels are low- and medium-carbon grades.

Special cold-heading quality applies to cold-finished alloy steel bars for applications involving severe cold plastic deformation when slight surface imperfections may cause splitting of a part. Bars of this quality are produced by closely controlled steelmaking practices to provide uniform chemical composition and internal soundness. Also, special processing (such as grinding) is applied at intermediate stages to remove detrimental surface imperfections. Proper control of hardness and microstructure by heat treatment and cold working is important for cold forming.

Axle shaft quality applies to cold-finished alloy steel bars intended for the manufacture of automotive or truck-type, power-driven axle shafts, which by their design or method of manufacture are either not machined all over or undergo less than the recommended amount of stock removal for proper cleanup of normal surface imperfections.

Ball and roller bearing quality and bearing quality apply to cold-finished alloy steel bars used for the manufacture of antifriction bearings. Such bars are usually produced from alloy steels of the SAE-AISI standard alloy carburizing grades and the SAE-AISI high-carbon chromium series. These steels can be produced in accordance with ASTM A 534, A 295, and A 485 (see the article "Bearing Steels" in this Section for details).

Aircraft quality and magnaflux quality apply to cold-finished alloy steel bars for important or highly stressed parts of aircraft and for other similar or corresponding purposes involving additional stringent requirements, such as magnetic particle inspection, additional discard, macroetch tests, and hardenability control.

Other Alloy Steel Qualities. The quality descriptors listed below apply to cold-finished alloy steel bars intended for rifles, guns, shell, shot, and similar applications. They may have requirements for amount of discard, macroetch testing, surface requirements, or magnetic particle testing as indicated in the product specifications:

- Armor-piercing (AP) shot quality
- AP shot magnaflux quality
- Gun quality
- Rifle barrel quality
- Shell quality
- Shell magnaflux quality

Mechanical Properties

A major difference between machined and cold-drawn round bars is the improvement in tensile and yield strengths that results from the cold work of drawing. Cold work also changes the shape of the stress-strain diagram, as shown in Fig. 3. Within the range of commercial drafts, cold work markedly affects certain mechanical properties (Fig. 4). The variations in percentage of reduction of cross section for bars drawn with normal commercial drafts of 0.8 and 1.6 mm ($\frac{1}{32}$ and $\frac{1}{16}$ in.) and with heavy drafts of 3.2 and 4.8 mm ($\frac{1}{8}$ and $\frac{3}{16}$ in.) are shown in Fig. 5. Normal reductions seldom exceed 20% and are usually less than 12%. According to Fig. 4, the more pronounced changes in significant tensile properties occur within this range of reductions (up to about 15%).

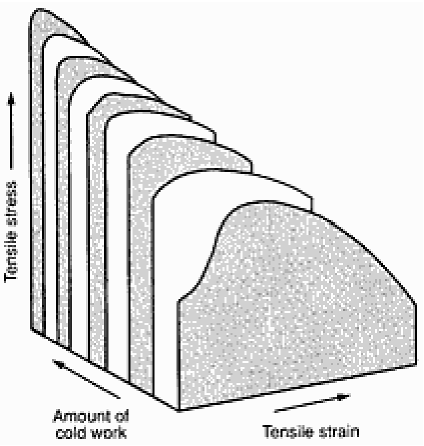


Fig. 3 Effect of cold work on the tensile stress-strain curve for low-carbon steel bars

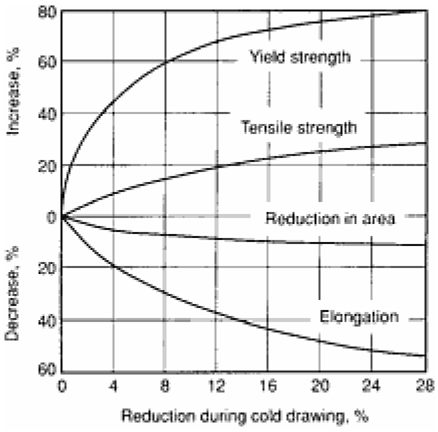


Fig. 4 Effect of cold drawing on the tensile properties of steel bars. Data are for bars up to 25 mm (1 in.) in cross section having a tensile strength of 690 MPa (100 ksi) or less before cold drawing.

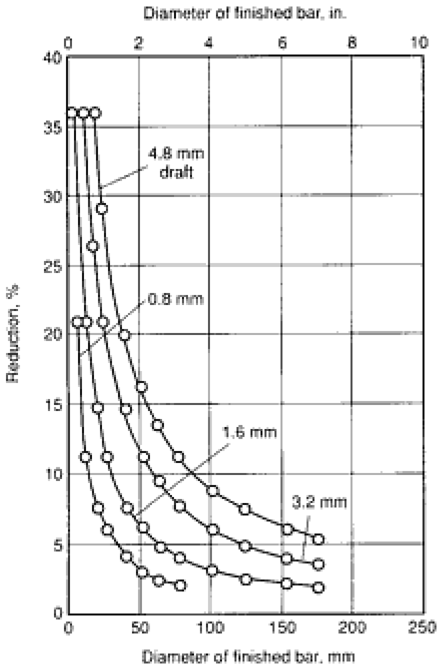


Fig. 5 Effect of draft on reduction of cross section of steel bars

Steel Wire Rod

WIRE ROD is a semifinished product rolled from billet on a rod mill and is used primarily for the manufacture of wire. The steel for wire rod is produced by all the steelmaking processes, including the basic oxygen, basic open hearth, and electric furnace processes. Steel wire rod is usually cold drawn into wire suitable for further drawing; for cold rolling, cold heading, cold upsetting, cold extrusion, or cold forging; or for hot forging.

Although wire rod may be produced in several regular shapes, most is round in cross section. Round rod is usually produced in nominal diameters of 5.6 to 18.7 mm ($\frac{7}{32}$ to $\frac{47}{64}$ in.), advancing in increments of 0.4 mm ($\frac{1}{64}$ in.). As the rod comes off the rolling mill, it is formed into coils. These coils are usually about 760 mm (30 in.) in inside diameter and weigh up to 2000 kg (4400 lb). The dimensions and maximum weight of a single coil are determined by the capabilities of the rolling mill. Coil weights that exceed the capabilities of the rolling mill sometimes can be obtained by welding two or more coils together. The standard tolerances are ±0.4 mm ($\pm\frac{1}{64}$ in.) on the diameter and 0.64 mm (0.025 in.) maximum out-of-roundness.

Producers of wire rod may market their product as rolled, as cleaned and coated, or as heat treated, although users generally prefer to do such preparations themselves. These operations are explained in the following sections, along with the several recognized quality and commodity classifications applicable to steel wire rods.

Processing

Cleaning and Coating. Mill scale is cleaned from steel wire rods by pickling or caustic cleaning followed by water rinsing, or by mechanical means such as shot blasting with abrasive particles or reverse bending over sheaves. The chemical cleaning of steel wire rods is always followed by a supplementary coating operation. Lime, borax, or phosphate coating is applied to provide a carrier for the lubricant necessary for subsequent processing into wire. In lime coating, practices may be varied in order to apply differing amounts of lime on the rods depending on the customer requirements. Phosphate-coated rods may have a supplementary coating of lime, borax, or water-soluble soap. Mechanically descaled rods may be drawn without coating using only wire drawing soaps, or may be coated in a fashion similar to that used for chemically cleaned rods.

Heat treatments commonly applied to steel wire rod, either before or during processing into wire, include annealing, spheroidize annealing, patenting, and controlled cooling. Annealing commonly involves heating steel wire rod to a temperature near or below the lower critical temperature and holding it at that temperature for a sufficient period of time, followed by slow cooling. This process softens the steel for further processing, but not to the same degree as does spheroidize annealing. Spheroidize annealing involves prolonged heating at a temperature near or slightly below the lower critical temperature (or thermal cycling at about the lower critical temperature), followed by slow cooling, in order to change the shape of carbides in the microstructure to globular (spheroidal), which produces maximum softness.

Patenting is a heat treatment usually confined to medium-high-carbon and high-carbon steels. In this process, individual strands of rod or wire are heated well above the upper critical temperature and then are cooled comparatively rapidly in air, molten salt, molten lead, or a fluidized bed. The object of patenting is to develop a microstructure of homogeneous, fine pearlite. This treatment generally is employed to prepare the material for subsequent wire drawing.

Controlled cooling is a heat treatment performed in modern rod mills in which the rate of cooling after hot rolling is carefully controlled. The process imparts uniformity of properties and some degree of control over scale, grain size, and microstructure.

Carbon Steel Rod

Compositions. Carbon steel rods are produced in various grades, or compositions:

- Low-carbon steel wire rods (maximum carbon content ≤ 0.15%)
- Medium-low-carbon steel wire rods (maximum carbon content >0.15% but ≤ 0.23%)
- Medium-high-carbon steel wire rods (maximum carbon content >0.23% but ≤ 0.44%)
- High-carbon steel wire rods (maximum carbon content >0.44%)

Ordinarily, sulfur and phosphorus contents are kept within the usual limits for each grade of steel, while carbon, manganese, and silicon contents are varied according to the mechanical properties desired. Occasionally, sulfur and/or phosphorus may be added to the steel to improve the machinability.

Qualities and Commodities. Rod for the manufacture of carbon steel wire is produced with manufacturing controls and inspection procedures intended to ensure the degree of soundness and freedom from injurious surface imperfections necessary for specific applications. The quality descriptors and commodities applicable to carbon steel wire rod are:

- Industrial quality rod
- Chain quality rod
- Fine wire quality rod
- Cold finishing quality rod
- Heading, cold extrusion, or cold rolling quality rod
- Wood screw quality rod
- Scrapless nut quality rod
- Severe cold heading, severe cold extrusion, or severe scrapless nut quality rod
- Welding quality rod
- Medium-high-carbon and high-carbon quality rod
- Special quality rod (e.g., rod for music wire, valve spring wire, and tire cord wire)

Mechanical Properties. In the older mills, where rod was coiled hot, there was considerable variation within each coil because of the effect of varying cooling rates from the center to the periphery of the coil. Therefore, as-hot-rolled rod was seldom sold to specific mechanical properties because of the inherent variations of such properties. These properties for a given grade of steel varied from mill to mill and were influenced by both the type of mill and the source of steel being rolled.

In newer rod mills, which are equipped with controlled cooling facilities, this intracoil variation is kept to a minimum. In such mills, finishing temperature, cooling of water, cooling air, and conveyor speed all are balanced to produce rod with the desired scale and microstructure. This structure, in turn, is reflected in the mechanical properties of the rod and permits the rod to be drawn directly for all but the most demanding applications. The primary source of intracoil variation on these new mills is the overlapping of the coiled rings on the conveyor. These overlapped areas cool at a slower rate than the majority of the ring.

Table 9 lists typical values of tensile strength for 5.6 mm ($\frac{7}{32}$ in.) low-carbon steel rod rolled on a modern rod mill equipped with controlled cooling facilities. The values shown are for rods rolled with full air cooling. Tensile strength values for larger-diameter rod are lower, decreasing by approximately 1.9 MPa (270 psi) for each 0.4 mm ($\frac{1}{64}$ in.) increment by which rod diameter exceeds 5.6 mm ($\frac{7}{32}$ in.). Similar analyses of rods rolled without full air cooling or rods rolled on an older mill, where the steel is coiled hot, would be expected to reveal lower tensile strength.

Table 9 Tensile strength of 5.6 mm ($\frac{7}{32}$ in.) diam hot-rolled low-carbon steel rod

Steel grade	Rimmed		Capped		Aluminum killed fine-grain steel		Silicon killed fine- or coarse-grain steel	
	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
1005	350	51	. . .	. . .	380	55	395	57
1006	360	52	365	53	395	57	405	59
1008	370	54	385	56	405	59	425	62

1010	385	56	400	58	420	61	440	64
1012	405	59	420	61	435	63	455	66
1015	425	62	440	64	450	65	475	69
1017	450	65	455	66	455	66	495	72
1018	. . .	. . .	475	69	490	71	525	76
1020	470	68	475	69	485	70	510	74
1022	. . .	. . .	. . .	. . .	520	75	565	82

Data obtained from rod produced with controlled cooling

Table 10 shows typical expected tensile strength values for 5.6 mm ($\frac{7}{32}$ in.) medium-high-carbon and high-carbon steel rods rolled on a mill utilizing controlled cooling.

Table 10 Tensile strength of 5.6 mm ($\frac{7}{32}$ in.) diam hot-rolled medium-high-carbon and high-carbon steel rod

Carbon content of steel, %	**Tensile strength for steel with manganese content of**					
	0.60%		**0.80%**		**1.00%**	
	MPa	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**
0.30	641	93	676	98	717	104
0.35	689	100	731	106	793	115
0.40	745	108	779	113	820	119
0.45	793	115	834	121	869	126
0.50	848	123	883	128	931	135
0.55	896	130	938	136	972	141
0.60	951	138	986	143	1020	148

0.65	1000	145	1041	151	1076	156
0.70	1055	153	1089	158	1124	163
0.75	1103	160	1138	165	1179	171
0.80	1151	167	1193	173	1227	178
0.85	1207	175	1241	180	1282	186

Data obtained from rod produced with controlled cooling

Alloy Steel Rod

Alloy steels are those steels for which maximum specified manganese content exceeds 1.65% or maximum specified silicon or copper content exceeds 0.60%; or for which a definite range or definite minimum quantity of any other element is specified in order to obtain desired effects on properties. For detailed information on composition ranges and limits of alloy steels, see the article "Classifications and Designations of Carbon and Alloy Steels," at the beginning of this Section.

Steel Wire

WIRE may be cold drawn from any of the types of carbon steel or alloy steel rod described in the preceding subsection on steel wire rod. For convenience in describing the various grades of carbon steel wire, they may be divided into the same four classes used for carbon steel wire rod. Based on carbon content, these classes are: low-carbon steel wire (0.15% carbon max), medium-low-carbon steel wire (>0.15 to 0.23% carbon), medium-high-carbon steel wire (>0.23 to 0.44% carbon), and high-carbon steel wire (>0.44% carbon). The conventional four-digit or five-digit SAE-AISI designation is used to specify the carbon or alloy steel used to make the wire. Carbon and alloy steel wire can be produced in qualities suitable for cold rolling, cold drawing, cold heading, cold upsetting, cold extrusion, cold forging, hot forging, cold coiling, heat treatment or carburizing, and for a wide variety of fabricated products.

Wire Shapes and Sizes

Shapes of Wires. Although wire ordinarily is thought of as being only round, it may have any one of an infinite number of sectional shapes, as required by end use. After ordinary round wire, the most common shapes are square, hexagonal, octagonal, oval, half-oval, half-round, triangular, and flat. Besides these regular (symmetrical) shapes, wire also is made in various odd and irregular shapes for specific purposes.

Sizes of Wire. The size limits for the product commonly known as wire range from approximately 0.13 mm (0.005 in.) to (but not including) 25.4 mm (1 in.) for round sections, and from a few tenths of a millimeter (a few thousandths of an inch) to approximately 13 mm ($\frac{1}{2}$ in.) for square sections. Larger rounds and squares, and all sizes of hexagonal and octagonal sections, are commonly known as bars.

Wiremaking Practices

Wiredrawing. Steel wire is produced from coils of wire rod after removal of scale by one or more cold reduction processes intended primarily for the purpose of obtaining the desired size. Wiredrawing, which improves surface finish and dimensional accuracy, is the most common cold reduction process. Cold drawing naturally results in mechanical and physical properties different from those of hot rolled steel of like composition. By varying the amount of cold reduction and other wire mill practices (including heat treatment) a wide diversity of properties and finishes can be obtained.

Mechanical characteristics of steel wire (e.g., strength, stiffness, hardness) result from wire mill treatment as well as from chemical composition, and thus mechanical properties of wire are less dependent on chemical composition than those of other steel mill forms. In most instances, the purchaser of wire is interested in suitability for a given application rather than in chemical composition.

Before drawing, the scale is removed from the material by acid pickling or mechanical descaling. If acid pickled, the coil is rinsed with water, dipped in a vat containing hydrated lime in suspension or other material in solution, and baked to dry the coating and to liberate any hydrogen that may have been absorbed by the steel during pickling.

In cold drawing of wire, coiled rod is drawn through the tapered hole of a die or through a series of dies, the number of dies employed depending on the finished diameter required. To begin drawing, one end of the rod is pointed, inserted through the die and attached to a power-driven reel (block); the block then pulls the material through the die and coils the drawn wire.

The common design of wiredrawing die (see Fig. 6) consists of a supporting ring of steel encasing a hard, wear-resistant nib. The nib consists of one or more carbides (such as tungsten, tantalum, or titanium) mixed with a bonding agent, such as cobalt, pressed into the desired shape and sintered into its hardened rough form, after which it is mounted, sized, and polished. For certain types of fine wire, diamond dies sometimes are used instead of carbide dies.

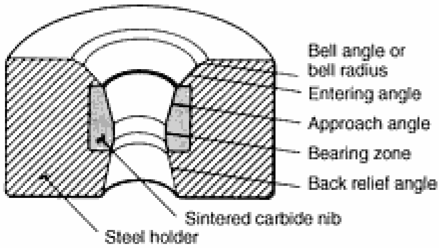


Fig. 6 Typical wiredrawing die: schematic cross section (not to scale) of a single-hole wiredrawing die employing a nib of sintered carbide mounted in a circular steel holder

The amount of reduction during drawing is expressed as a percent of the original cross-sectional area and is known as draft. As soon as a wire rod has been reduced by drawing, it is called a wire, even though many more reductions (drafts) may be necessary to reduce it to final size.

Cleaning and Coating. Whenever necessary, scale and other surface contaminants are cleaned from steel wire by acid pickling followed by water rinsing. Cleaning is always followed by a supplementary coating operation.

Lime, borax, or phosphate coating is performed to provide a carrier for the lubricant necessary for subsequent processing. In lime coating, practices may be varied to apply differing amounts of lime, depending on the end use. Phosphate-coated wire may have a supplementary coating of lime, borax, or a water-soluble soap.

Heat treatments for steel wire include annealing, patenting, and oil tempering.

Annealing-in-process is performed on dry drawn low-carbon or medium-low-carbon steel wire. The product is sometimes called "processed wire" or "bright soft wire." In producing annealed-in-process wire, an annealing heat treatment (followed by a separate cleaning and coating operation) is performed at an intermediate stage of wiredrawing to produce a softer wire for applications in which direct drawn wire would be too hard or too stiff.

Patenting is a thermal treatment usually confined to medium-high-carbon and high-carbon steels. In this process, individual strands of rod or wire are heated well above the upper critical temperature and then cooled comparatively rapidly in air, molten salt, or molten lead. This treatment is generally employed to prepare the material for subsequent wiredrawing.

Oil tempering is a heat treatment for high-carbon steel wire in which strands of the wire at finish size are continuously heated to an appropriate temperature above the critical temperature range, oil quenched, and finally passed through a tempering bath. Oil tempering is used in the production of such commodities as oil-tempered spring wire, which is used in certain types of mechanical springs that are not subjected to a final heat treatment after forming.

Specification Wire

There are some applications for low-carbon and medium-low-carbon steel wire that involve special requirements, such as specific tensile strength ranges or hardness limitations, the attainment of which involves special selection of steel and modification of conventional wire mill practices and/or thermal treatment (for example, annealed in-process wire). Such wire is commonly designated specification wire.

A standard specification that covers the general requirements for coarse, carbon steel round wire is ASTM A 510 (Table 11). Specification wire can be furnished with special finishes for subsequent processing, such as spot welding, electroplating, and tinning.

Table 11 Common tensile strength ranges for coarse, round specification wire

Wire diameter		**Tensile strength range**[a]	
mm	**in.**	**MPa**	**ksi**
0.889 to <2.69	0.035 to <0.106	207	30
2.69 to 4.50	0.106 to 0.177	172	25
>4.50	>0.177	138	20

(a) Difference between specified minimum and maximum values

Metal-Coated Wire

Metallic coatings can be applied to wire by various methods, including both hot dip processes' and electrolytic processes.

Aluminized wire (aluminum-coated wire) is produced by passing strands of wire through a bath of molten aluminum or aluminum alloy.

Brass-plated wire is produced by passing strands of wire through an electrolytic cell containing a solution of both copper and zinc salts. Generally, such wire is used when rubber adhesion is required or when pleasing appearance is important. Brass-plated wire is not intended for applications requiring corrosion resistance.

Galvanized wire (zinc-coated wire) is produced by passing strands of wire through a bath of molten zinc (hot dip galvanized) or through an electrolytic cell containing a solution of a zinc salt (electrogalvanized). The wire usually is annealed in the same operation by being passed through molten lead, molten salt, or a furnace, followed by cleaning or pickling, prior to galvanizing. The general requirements for galvanized carbon steel wire are given in ASTM A 641.

The term "temper" as applied to galvanized wire is a reference to stiffness or resistance to bending, not to heat treatment. It customarily is expressed as soft, medium, or hard. Tensile strengths corresponding to these three tempers are given in Table 12.

Table 12 Tensile strength ranges and limits of galvanized wire

Wire diameter		Tensile strength					
		Soft temper (maximum)[a]		Medium temper		Hard temper	
mm	in.	MPa	ksi	MPa	ksi	MPa	ksi
0.889 to <2.03	0.035 to <0.080	515	75	483-690	70-100	620-825	90-120
2.03 to <2.69	0.080 to <0.106	515	75	483-655	70-95	585-795	85-115
2.69 to 4.47	0.106 to 0.176	483	70	448-620	65-90	550-760	80-110
>4.47	>0.176	483	70	414-585	60-85	515-720	75-105

(a) Generally produced from maximum 0.13% C grades

Tinned wire is produced by passing strands of wire continuously through a molten tin bath and then through tightly compressed wipes as the strands emerge from the bath. Tinned wire is commonly manufactured in three tempers: soft, medium hard, and hard. Soft tinned wire is tinned after being annealed at or near finish size. Medium-hard tinned wire is produced from heat treated wire. Hard tinned wire is obtained by tinning wire that has been cold drawn to final size, usually without intermediate heat treatment.

Quality Descriptors and Commodities

Many kinds of steel wire have been developed for specific components of machines and equipment and for particular end uses. The unique properties of each of these types of wire are obtained by employing a specific combination of steel composition, steel quality, process heat treatment, and cold drawing practice.

These wires normally are grouped into broad usage categories including:

- Low-carbon steel wire for general usage
- Wire for packaging and container applications (includes bailing wire and strapping wire)
- Wire for structural applications (includes galvanized bridge wire, zinc- and aluminum-coated strand wire, and concrete reinforcing wire)
- Wire for prestressed concrete
- Wire for electrical or conductor applications (includes aluminum conductor steel reinforced wire and telephone and telegraph wire)
- Rope wire

Wire for Fasteners

Wire for fasteners includes wire intended for such applications as bolts and cap screws, rivets, wood and self-tapping screws, and scrapless nuts. Depending on the application, such wire must be able to be forged, extruded, cold upset, roll or cut threaded, drilled, and hardened by suitable heat treatment.

The type and grade of steel used in wire for fasteners depend on the requirements of the finished product and the nature of the required forming operations. Compositions range from that of 1006 steel, which is used for such items as common rivets, to that of a 0.55 to 0.65% carbon steel intended for lockwashers or screwdrivers. The wire may be drawn from hot rolled or annealed wire rod, and it may be either annealed or spheroidized in process.

The coating on the wire must provide sufficient lubrication in the header dies and must have the necessary lubricating qualities to prevent galling or undesirable die wear. Although lime-soap coatings are common, phosphate coatings are frequently used for more demanding applications. Producing phosphated wire may involve coating the cleaned rod or process wire with zinc phosphate and then coating with lime or borax to carry the lubricant during subsequent drawing.

It is important that the wire be internally sound and free from seams and other surface imperfections. Decarburization must be held to a minimum for those products that are to be hardened by heat treatment.

Mechanical Spring Wire for General Use

The several types of steel wire used for mechanical springs are produced in a variety of chemical compositions, but the primary consideration is that the wire have the specific properties necessary for the application. The required properties vary with the intended use of the spring and with problems involved in its fabrication. Among the factors governing the selection of spring wire are: (a) the load range through which the spring must operate; (b) the corresponding stress range for the wire; (c) weight and space limitations; (d) expected life of the spring; (e) temperatures and other environmental conditions to be encountered in service; and (f) severity of deformation to be encountered in fabrication.

As stress on the wire is increased, wire with higher strength is required. Because the surface of the wire is the most highly stressed part of a spring, freedom from surface imperfections becomes increasingly important as maximum stress or required service life is increased. Surface condition is very important in music spring steel wire and is even more important in valve spring quality wire.

There are three types of spring wire for general use: hard drawn spring wire (covered in ASTM A 227 and A 679), oil tempered spring wire (ASTM A 229) and spring steel wire for heat treated components (ASTM A 713).

Music spring steel wire is used in springs subject to high stresses and requiring good fatigue properties. Final cold drawing commonly is performed by the wet white liquor method to develop a characteristic smooth bright luster. Manufacturers employ specialized coiling tests, twist tests, torsion tests and bend tests to verify that the exacting requirements of this type of wire are met. ASTM A 228 describes music spring steel wire in detail.

Fine Wire

Fine wire is considered to include all wire less than 0.89 mm (0.035 in.) in diameter, as well as some coarser wire up to 1.57 mm (0.062 in.) in diameter when so designated. Fine wire commonly is produced with bright, liquor, coppered, or phosphate finishes; with galvanized, tin, or cadmium coatings; and in the hard drawn, annealed, or oil-tempered conditions. Aircraft cords, brooms, brushes, fishhooks, florist wire, hose reinforcement, paper clips, insect screens, and safety pins are examples of products produced entirely or in part from various kinds of fine wire.

Aircraft cord wire is a hard drawn, high-tensile-strength, high-carbon steel wire designed for manufacture of flexible cords and multiple-wire strands for aircraft controls.

Alloy Wire

Chemical compositions and quality descriptions, as well as requirements and tests, applicable to alloy wire are described in the preceding article on steel wire rod. Many alloy steel wires have been developed for specific applications which include wires for bearings, chains and springs, and for cold heading and cold forging applications.

Alloy steel spring wire is used for the manufacture of springs intended for operation at moderately elevated temperatures. Three grades in common use are 6150 chromium-vanadium steel, SAE 9260 silicon manganese, and 9254 chromium-silicon steel, which are covered in ASTM A 231, A 232, and A 401, respectively. ASTM A 877/A 877M also covers chromium-silicon grades; ASTM A 878/A 878M covers a grade of modified chromium-vanadium steel valve spring quality wire.

The wire is commonly produced in one of four conditions: oil tempered, spheroidize annealed, annealed in-process, and patented in-process. Oil-tempered alloy spring wire, commonly produced in diameters up to 12.7 mm (0.500 in.) to tensile strength or hardness requirements, is intended for very light forming and is generally used for coiling into common types of springs. Table 13 lists tensile strength ranges for several oil-tempered wires.

Table 13 Tensile strength ranges for oil-tempered alloy steel spring wires

Wire diameter[(a)]		**Chromium-vanadium spring wire, aircraft quality spring wire, and valve-spring quality wire**		**Chromium-silicon spring wire**	
mm	**in.**	**MPa**	**ksi**	**MPa**	**ksi**
0.51	0.020	2070-2240	300-325	. . .	. . .
0.89	0.035	2000-2170	290-315	2070-2240	300-325
1.22	0.048	1930-2100	280-305	2030-2200	295-320
1.57	0.062	1830-2000	265-290	2000-2170	290-315
1.83	0.072	1790-1930	260-280	1990-2160	288-313
2.03	0.080	1760-1900	255-275	1960-2140	285-310
2.34	0.092	1720-1860	250-270	1930-2100	280-305
2.68	0.105	1690-1830	245-265	1900-2070	275-300
3.43	0.135	1620-1760	235-255	1860-2030	270-295
4.11	0.162	1550-1690	225-245	1830-2000	265-290
4.88	0.192	1520-1660	220-240	1790-1950	260-283
6.35	0.250	1450-1590	210-230	1720-1900	250-275
7.19	0.283	1410-1550	205-225	1710-1880	248-273
7.94	0.312	1400-1540	203-223	1690-1860	245-270
9.52	0.375	1380-1520	200-220	1660-1830	240-265
11.12	0.438	1340-1480	195-215	1620-1790	235-260

12.70	0.500	1310-1450	190-210	. . .	. . .

(a) For diameters other than those shown in the above table, tensile strengths may be determined by interpolation.

Steel Tubular Products

Introduction

STEEL TUBULAR PRODUCTS is the term used to cover all hollow steel products. Although these products are usually produced in cylindrical form, they are often subsequently altered by various processing methods to produce square, oval, rectangular, and other symmetrical shapes. Such products have applications that are almost innumerable, but they are most commonly used as conveyors of fluids and as structural members.

Product Classification

The two simplest and broadest commercial classifications of steel tubular products are tube and pipe. (Although the application of the terms pipe and tube is not always consistent, the term pipe is commonly used to describe cylindrical tubular products made to standard combinations of outside diameter and wall thickness.) These two broad classifications are subdivided into several named use groups. For example, the term tube covers three such groups: pressure tubes, structural tubing, and mechanical tubing.

The term pipe covers five such groups: standard pipe, line pipe, oil country tubular goods, water well pipe, and pressure pipe. There is also pipe for special applications, such as conduit pipe and tubular piling, that do not fit any of these classifications. Each of these use groups, in turn, has a number of uses or named-use subdivisions. These are shown in Table 1.

Table 1 Major types and uses of pipe

Type of pipe	**Uses**
Standard	Industrial or residential water steam, oil, or gas transmission; distribution or service lines; structural uses
Special	Conduit, piling, pipe for nipples, and other
Line	Oil- or gas-transmission pipe, water-main pipe
Oil country tubular goods	Drill pipe, casing, tubing
Water well	Drive pipe, driven-well pipe, casing, reamed pipe, and drifted pipe
Pressure	Pipe for elevated-temperature or pressure service

The named uses in Table 1 have been developed without regard to method of manufacture, size range, wall thickness, or degree of finish. For example, the names do not distinguish between those products commonly called pipe that have size and wall thicknesses the same as standard pipe, and those having different basic dimensions; all are termed pipe.

On a use basis, pressure pipe is distinguished from pressure tubes in that the latter are suitable for those applications in which heat is applied externally. The principal use groups and types of pressure tubes are shown in Table 2.

Table 2 Principal uses and types of pressure tubes

Use groups	**Types**
Water tube boilers	Generating tubes, superheater tubes, economizer tubes, circulator tubes, furnace wall tubes
Fire tube boilers	Boiler flues, superheater flues, superheater tubes, arch tubes, stay tubes, safe ends
Others	Feedwater heater tubes, oil still tubes

Structural and mechanical tubing do not follow this system of nomenclature. Instead, their names are derived from the method of fabrication and degree of finish, such as cold formed welded or seamless hot finished.

Steel tubular products can be made by forming a flat skelp, sheet, strip, or plate into a hollow cylinder and welding the resulting longitudinal seam together or by generating an opening in a solid cylinder by piercing and elongating the resultant hollow cylinder. The first group of products is called welded and the second group, seamless.

Welding Processes

In producing welded steel tubular products, flat-rolled skelp, strip, sheet or plate is formed into cylinders that are then joined at the longitudinal or spiral seam by one of the processes described below.

Electric resistance welding employs a series of operations, in the first of which the flat-rolled steel is cold shaped into tubular form. Welding is effected by the application of pressure and heat generated by induction or by an electric current through the seam. The welding pressure is generated by constricting rolls and the electromagnetic effects of the high welding current. Electric resistance welded tubular products having longitudinal seams are usually made in sizes ranging from 3.2 mm ($\frac{1}{8}$ in.) nominal to 0.6 m (24 in.) actual outside diameter, but larger sizes are also available. Electric resistance methods are also sometimes used for making tubular products by spiral welding. This method is frequently used for large-diameter products.

Continuous Welding. In continuous (or furnace butt) welding, skelp with square or slightly beveled edges is furnace heated to the welding temperature. The heated stock is roll formed into cylindrical shape as it emerges from the furnace; additional heat is usually provided by an oxygen or air jet impinging on the seam edges, and the tube passes through constricting rolls where the seam edges are welded by the pressure of the rolls. Continuous welded products are available in nominal diameters from 3.2 to 100 mm ($\frac{1}{8}$ to 4 in.).

Fusion Welding. In fusion welding, the flat-rolled steel, with edges suitably prepared, is formed into tubular shape by either hot or cold shaping. The flat-rolled steel may be shaped longitudinally (straight seam) or bent into helical form (spiral welded). The edges are welded with or without simultaneously depositing filler metal in a molten or molten-and-vapor state. Mechanical pressure is not required to effect welding. Fusion may be accomplished by either electric arc or gas heating, or a combination of both. The upper limit of outside diameter is determined mainly by the forming method and the fusion welding process used.

Double submerged arc welding is a special method of shielded-arc welding in which the seam is submerged under a solid flux while being welded. The weld is made in two passes, one from inside the pipe and the other from outside the pipe, with approximately half the wall thickness being welded in each pass. The maximum diameter is limited only by the capability of the forming equipment, and double submerged-arc welded pipe is currently available in outside diameters of up to 3 m (120 in.).

Seamless Processes

Steel tubular products produced by the seamless processes are made in diameters up to 0.67 m (26 in.) by the rotary piercing method and up to 1.2 m (48 in.) by hot extrusion.

Rotary Piercing. In rotary piercing, rounds of the necessary diameter and length are first heated to rolling temperature. Each hot round is fed into a set of rolls having crossed axes and surface contours that pull it through the rolls, thus rupturing it longitudinally. The force of the rolls then causes the metal to flow around a piercing point, enlarging the axial hole, smoothing the inside surface, and forming a tube. After being pierced, the rough tube is usually hot rolled to final dimensions by means of plug mills or mandrel mills, which may be followed by stretch reducing mills.

Hot extrusion is a hot working process for making hollows, suitable for processing into finished tubing of regular and irregular form, by forcing hot, prepierced billets through a suitably shaped orifice formed by an external die and internal mandrel. The outside of the hollow acquires the size and contour imposed by the die; the inside conforms to the size and contour of the mandrel. Extruded hollows may be further worked into tubular products by cold-finishing methods.

Cupping and Drawing. In the cupping and drawing method of making seamless tubing, a circular sheet or plate is hot cupped in a press through several pairs of conical dies, each successive pair being deeper and more nearly cylindrical than the previous set. The rough tube then is drawn to finished size.

Cold Finishing

Pipe in suitable sizes and most products classified as tubing, both seamless and welded, may be cold finished. The process may be used to increase or decrease the diameter, to produce shapes other than round, to produce a smoother surface or closer dimensional tolerances, or to modify mechanical properties. The process most commonly used is cold drawing, in which the descaled hot-worked tube is plastically deformed by drawing it through a die and over a mandrel (mandrel drawing) to work both exterior and interior surfaces. Cold drawing through the die only (without a mandrel) is called sink drawing or sinking.

Tube Reducing and Swaging. In tube reducing by rotorolling or pilgering and in swaging, a reducing die works the tube hollow over a mandrel; swaging may, however, be done without a mandrel. The commercial importance of tube reducing is, first, that very heavy reductions (up to 85%) can be applied to mill length tubes, and second, that the process can be applied to the refractory alloys that are difficult to cold draw because of high power requirements.

Cold Finishing. Tubular products of circular cross section may be cold finished on the outside by turning, grinding, or polishing, or by any combination of these processes. They may be bored, skived, or honed on the inside diameter. Because these operations involve stock removal only, with negligible plastic deformation, there is no enhancement of mechanical properties.

Many of the standard specifications involving strength are based on the properties of hot-rolled or cold-worked material. Some high-strength oil country goods are heat treated to achieve the combination of high strength, ductility, and sulfide stress corrosion cracking resistance required by the intended application.

Cold drawing may be employed to improve surface finish and dimensional accuracy and to increase the strength of tubular products. Some customer specifications prescribe strength levels that can best be attained by cold working.

Pipe Sizes and Specifications

Pipe is distinguished from tubing by the fact that is produced in relatively few sizes and, therefore, in comparatively large quantities of each size. For a reasonably complete list of the standardized sizes and weights of pipe for the major named uses, the AISI Steel Products Manual should be consulted. For oil country tubular goods, the specifications of the American Petroleum Institute (API) govern. Table 3 lists the current ASTM, API, and Canadian Standards Association (CSA) specifications covering pipe. Some of these involve several grades. The specifications listed cover carbon high-strength low-alloy (HSLA), and alloy steels other than stainless, all methods of manufacture, and a wide range of service temperature. Steels are produced with yield strengths ranging from 170 MPa to 930 MPa (25 to 135 ksi).

Table 3 ASTM, API, and CSA specifications for carbon, HSLA, and alloy steel pipe

Specification	Product
ASTM specifications	
A 53[a]	Welded and seamless steel pipe, black and hot dipped, zinc coated
A 106[a]	Seamless carbon steel pipe for high-temperature service
A 134[a]	Arc-welded steel-plate pipe (sizes 400 mm, or 16 in., and over)
A 135[a]	Resistance-welded steel pipe
A 139	Arc-welded steel pipe (sizes 100 mm, or 4 in., and over)

A 211	Spiral-welded steel or iron pipe
A 252	Welded and seamless steel pipe piles
A 333[(a)]	Welded and seamless steel pipe for low-temperature service
A 335[(a)]	Seamless ferritic alloy steel pipe for high-temperature service
A 381	Double submerged-arc welded steel pipe for high-pressure transmission systems
A 405	Seamless ferritic alloy steel pipe, specially heat treated for high-temperature service
A 523	Resistance-welded or seamless steel pipe (plain end) for high-pressure electric cable conduit
A 524[(a)]	Seamless carbon steel pipe for atmospheric service and lower temperatures
A 587[(a)]	Resistance-welded low-carbon steel pipe for the chemical industry
A 589	Welded and seamless carbon steel water well pipe
A 671[(a)]	Arc-welded steel pipe for atmospheric service and lower temperatures
A 672[(a)]	Arc-welded steel pipe for high-pressure service at moderate temperatures
A 691	Arc-welded carbon or alloy steel pipe for high-pressure service at high temperatures
A 714	Welded and seamless HSLA steel pipe
A 795	Black and hot-dipped zinc-coated (galvanized) welded and seamless steel pipe for fire protection use
API specifications	
2B	Specification for fabricated structural steel and pipe
5CT	Specification for casing and tubing
5D	Specification for drill pipe
5L	Specification for line pipe
CSA standard	

CAN3-Z245.1-M86	Steel line pipe

(a) This ASTM specification is also published by ASME, which adds an "S" in front of the "A" (for example, SA 53).

Common Types of Pipe

The following brief descriptions concern the end uses of some of the more common types of pipe.

Standard pipe is standard weight, extra strong, and double extra strong welded, or seamless pipe of ordinary finish and dimensional tolerances, produced in sizes up to 660 mm (26 in.) in nominal diameter, inclusive. This pipe is used for fluid conveyance and some structural purposes.

Conduit pipe is welded or seamless pipe intended especially for fabrication into rigid conduit, a product used for the protection of electrical wiring systems.

Piling pipe is welded or seamless pipe for use as piles, with the cylinder section acting as a permanent load-carrying member or as a shell to form cast-in-place concrete piles.

Pipe for nipples is standard weight, extra strong, or double extra strong welded or seamless pipe, produced for the manufacture of pipe nipples.

Transmission or line pipe is welded or seamless pipe currently produced in sizes ranging from 3 mm ($\frac{1}{8}$ in.) nominal to 1.2 m (48 in.) actual outside diameter and is used principally for conveying gas or oil. Transmission pipe, which is covered by API Specification 5L and CSA specification Z245.1 is being increasingly manufactured from microalloyed HSLA steels with yield strengths as high as 550 MPa (80 ksi).

Water main pipe is welded or seamless steel pipe used for conveying water for municipal and industrial purposes. Pipe lines for such purposes are commonly designated as flow mains, transmission mains, force mains, water mains, or distribution mains. The mains are generally laid underground.

Oil country tubular goods is a collective term applied in the oil and gas industries to three kinds of pipe used in oil wells: drill pipe, casing, and tubing. These products conform to API specifications 5CT (casing and tubing) and 5D (drill pipe).

Drill pipe is used to transmit power by rotary motion from ground level to a rotary drilling tool below the surface and to convey flushing media to the cutting face of the tool. Drill pipe is produced in sizes ranging from 60 to 170 mm ($2\frac{3}{8}$ to $6\frac{5}{8}$ in.) in outside diameter. Size designations refer to actual outside diameter and weight per foot. Drill pipe is usually upset, either internally or externally, or both, and is prepared to accommodate welded-on types of joints.

Casing is used as a structural retainer for the walls of oil or gas wells, to exclude undesirable fluids, and to confine and conduct oil or gas from productive subsurface strata to ground level. Casing is produced in sizes from 115 to 500 mm ($4\frac{1}{2}$ to 20 in.) in outside diameter.

Tubing is used within the casing of oil wells to conduct oil and gas to ground level. It is produced in sizes from 26 to 114 mm (1.05 to 4.50 in.) in outside diameter, in several weights per foot. Ends are threaded for special integral-type joints or fitted with couplings and may or may not be upset externally.

Water well pipe is a collective term applied to four types of pipe that are used in water wells and that conform to ASTM A 589: type I, drive pipe; type II, reamed and drifted pipe; type III, driven well pipe; and type IV, casing pipe.

Drive pipe is used to transmit power from ground level to a rotary drill tool below the surface and to convey flushing media to the cutting face of the tool. The lengths of pipe have specially threaded ends that permit the lengths to butt inside the coupling. Drive pipe is produced in nominal sizes of 150, 200, 300, 350, and 400 mm (6, 8, 12, 14, and 16 in.) in outside diameter.

Driven well pipe is threaded pipe in short lengths used for the manual driving of a drill tool or for use with short rigs. It may be furnished in random lengths ranging from 0.9 to 1.8 m (3 to 6 ft) or in random lengths ranging from 1.8 to 3.0 m (6 to 10 ft).

Casing is used both to confine and conduct water to ground level and as a structural retainer for the walls of water wells. It is produced as threaded pipe in random lengths from 4.9 to 6.7 m (16 to 22 ft) and in sizes from 90 to 220 mm ($3\frac{1}{2}$ to $8\frac{5}{8}$ in.) in outside diameter. In western water well practice, welded strings are sometimes used.

Reseamed and drifted pipe is similar to casing, but is manufactured and inspected in a manner that assures the well driller that the pipe string will have a predetermined minimum diameter sufficient to permit unrestricted passage of pumps or other equipment through the string.

Pressure pipe, as distinguished from pressure tubes, is a commercial term for pipe that is used to convey fluids at elevated temperature or pressure, or both, but that is not subjected to the external application of heat. This commodity is not differentiated from other types of pipe by ASTM, and the applicable specifications are listed with the other types in Table 3. Pressure pipe ranges in size from 3 mm ($\frac{1}{8}$ in.) nominal to 660 mm (26 in.) actual outside diameter in various wall thicknesses.

Pressure Tubes

Pressure tubes are given a separate classification by both ASTM and the producers. Pressure tubes are distinguished from pressure pipe in that they are suitable for application of external heat while conveying pressurized fluids.

The principal named uses of pressure tubing are given in Table 2. These tubings are produced to actual outside diameter and minimum or average wall thickness (as specified by the purchaser) and may be hot finished or cold finished, as specified.

Double-wall brazed tubing is a specialty tubing confined to small sizes (refer to ASTM A 254) It is used in large quantities by the automotive industry for brake lines and fuel lines, and by the refrigeration industry for refrigerant lines. It is made by forming copper-coated strip into a tubular section with double walls, using either single-strip or double strip construction. The tubing is then heated in a reducing atmosphere to join all mating surfaces completely. The resulting product is thus copper coated both inside and outside. When required by the intended service, a tin coating may be supplied. Available sizes range from 3 to 15 mm ($\frac{1}{8}$ to $\frac{5}{8}$ in.) in outside diameter (OD) with wall thickness from 0.64 mm (0.025 in.) for 3 mm ($\frac{1}{8}$ in.) OD to 0.9 mm (0.035 in.) for 15 mm ($\frac{5}{8}$ in.) OD.

Structural Tubing

Structural tubing is used for the welded, riveted, or bolted construction of bridges and building and for general structural purposes. It is available in round, square, rectangular, or special-shape tubing, as well as tapered tubing. These products are covered by ASTM specifications.

Mechanical Tubing

Mechanical tubing includes welded and seamless tubing used for wide variety of mechanical purposes. It is usually produced to meet specific end-use requirements and therefore is produced in many shapes, to a variety of chemical compositions and mechanical properties, and with hot-rolled or cold-finished surfaces. Most mechanical tubing is ordered to ASTM specifications. Even when customer specifications are used, they usually reference portions of the ASTM standard.

Mechanical tubing is not produced to specified standard sizes: instead, it is produced to specified dimensions, which may be anything the customer requires within the limits of production equipment or processes.

Welded mechanical tubing is usually made by electric resistance welding, but some is made by the various fusion welding processes. In all instances, the exterior welding flash may be removed (if necessary) by cutting, grinding, or hammering.

Electric resistance welded (ERW) mechanical tubing is made from hot-rolled or cold-rolled carbon steel or from alloy steel strip. The welded tubing can be supplied as-welded, hot finished, or cold finished. Sizes produced by ERW range in outside diameters from 6.4 to 400 mm ($\frac{1}{4}$ to 16 in.) and in wall thickness from 1.65 to 17 mm (0.065 to 0.680 in.) for hot-rolled steel and 0.65 to 4.2 mm (0.025 to 0.165 in.) for cold-rolled steel.

Continuous-welded cold-finished mechanical tubing, as its name implies, is tubing that has been hot formed by furnace butt welding and cold finished. It is furnished sink drawn or mandrel drawn and is available in outside diameters up to 90 mm ($3\frac{1}{2}$ in.) and wall thicknesses from 0.9 to 13 mm (0.035 to 0.500 in.). The material is low-carbon steel, and the product is, in effect, a form of cold-drawn pipe. Although furnished in a narrower size range than electric resistance welded tubing, it has two advantages: within the available size range, heavier walls are available, and there is no problem with flash.

Seamless mechanical tubing, both hot and cold finished, is available in a wide variety of finishes and mechanical properties. It is made from carbon and alloy steels in sizes up to and including 325 mm ($12\frac{3}{4}$ in.) OD.

Closed-Die Steel Forgings

Introduction

FORGING is the process of working hot metal between dies, usually under successive blows and sometimes by continuous squeezing. Closed-die forgings, hot upset parts, and extrusions are shaped within a cavity formed by the closed dies.

Justification for selecting forging in preference to other and sometimes more economical methods of producing useful shapes is based on several considerations. Mechanical properties in wrought materials are maximized in the direction of major metal flow during working.

Types of Forgings

Forgings are classified in several ways, beginning with the general classifications "open-die" and "closed-die." They are also classified in terms of the "close-to-finish" factor, or the amount of stock (cover) that must be removed from the forging by machining to satisfy the dimensional and detail requirements of the finished part (Fig. 1). Finally, forgings are classified in terms of the forging equipment required for their manufacture: for example, hammer upset forgings, ring-rolled forgings and multiple-ram press forgings (see the Section "Forging" in this Handbook for more detailed information on such equipment).

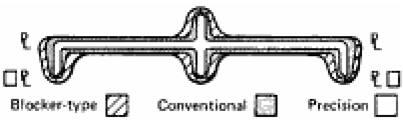


Fig. 1 Schematic composite of cross sections of blocker-type, conventional, and precision forgings

Of the various classifications, those based on the close-to-finish factor are most closely related to the inherent properties of the forging, such as strength and resistance to stress corrosion. In general, the type of forging that requires the least machining to satisfy finished-part requirements has the best properties. For this reason, a finished part that is machined from a blocker-type forging usually exhibits mechanical properties and corrosion characteristics that are inferior to those of a part produced from a close-tolerance, no-draft forging.

Selection of Steel

Selection of a steel for a forged component is an integral part of the design process, and acceptable performance is dependent on this choice. A thorough understanding of the end use of the finished part will serve to define the required mechanical properties, surface-finish requirements, tolerance to nonmetallic inclusions, and the attendant inspection methods and criteria.

Forging-quality steels are produced to a wide range of chemical compositions by electric furnace, open hearth, or pneumatic steelmaking processes.

Forgeability describes the relative ability of a steel to flow under compressive loading without fracturing. Except for resulfurized and rephosphorized grades, most carbon and low-alloy steels are usually considered to have good forgeability. Differences in forging behavior among the various grades of steel are small enough that selection of the steel is seldom affected by forging behavior. However, the choice of a resulfurized or rephosphorized steel for a forging is usually justified only if the forging must be extensively machined; because one of the principal reasons for considering manufacture by forging is the avoidance of subsequent machining operations, this situation is uncommon.

Design Requirements. Selection of a steel for a forged part usually requires some compromise between opposing factors; for instance, strength versus toughness, stress-corrosion resistance versus weight, manufacturing cost versus useful load-carrying ability, production cost versus maintenance cost, and the cost of the steel.

Material selection also involves consideration of melting practices, forming methods, machining operations, heat-treating procedures, and deterioration of properties with time in service, as well as the conventional mechanical and chemical properties of the steel to be forged.

An efficient forging design obtains maximum performance from the minimum amount of material consistent with the loads to be applied, producibility, and desired life expectancy. To match a steel to its design component, the steel is first appraised for strength and toughness and then qualified for stability to temperature and environment. Optimum steels are then analyzed for producibility and finally for economy.

Cost. The cost of steel as a percentage of the total manufacturing cost of forgings is shown in Fig. 2. These curves are based on an average of many actual forgings that are different in number of forging and heat treating operations required, cost of steel, quantity, and setup cost. It should not be inferred from these data that an average 14 kg (30 lb) stainless steel forging will cost 34% more than an average carbon steel forging of the same weight.

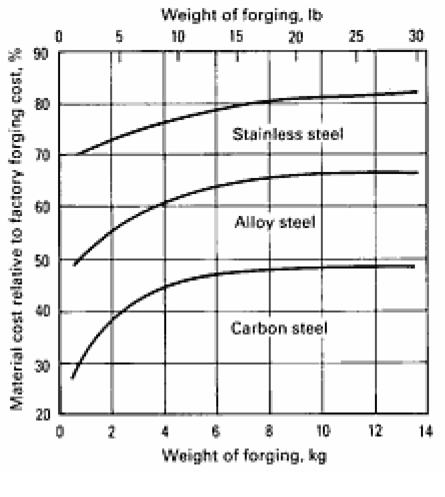


Fig. 2 Cost of steel as a percentage of total cost of forgings

Material Control

After completion of a forging design, there remains the responsibility of ensuring and verifying that the delivered forging will have all of the properties and characteristics specified on the forging drawing.

Responsibility for material control is subject to agreement between the purchaser and forging supplier. In many such agreements, the purchaser is responsible for design, material selection, and controls during manufacture; the forging supplier is responsible for performing raw-material inspection as well as maintaining adequate process control and product inspection.

Tests and Test Coupons. Tests contained in the material specifications are intended to provide correlation with, and interpretation of, the behavior of material in actual use. The dynamic behavior of a full-size structural component seldom can be accurately predicted from simple room-temperature tests on small specimens. Analytical studies coupled with model or full-scale testing can augment simple tests in interpreting the complex behavior of materials.

The kinds of test specimens and tests specified for quality assurance depend on the conditions imposed on the final component in service. If, for example, a critical forging is to be subjected to large tensile loads, the designer would specify tests to measure fracture toughness and tensile yield strength, For components for elevated-temperature service, tests measuring strength, ductility, and creep at appropriate temperatures would be specified.

Test Plans. Frequently, specifications are prepared from the results of tests on laboratory specimens because the cost and time required for full-scale testing are usually prohibitive. Test plans for evaluation of the mechanical properties of two high-strength 9Ni-4Co steels used in aircraft service at temperatures ranging from -45 to greater than 205 °C (-50 to greater than 400 °F) are shown in Table 1. This table illustrates the range and number of tests required for a very extensive type of evaluation.

Table 1 Testing plan for determining mechanical properties of forging material

Temperature and test	**Number of tests for[(a)]:**							
	9Ni-4Co-0.30C steel (1520-1660 MPa, or 220-240 ksi)[(b)]				**9Ni-4Co-0.45C steel (1790-1930 MPa, or 260-280 ksi)[(c)]**			
	L	**LT**	**ST**	**Total**	**L**	**LT**	**ST**	**Total**
At -80 °C (-110 °F)								
Tension	2	3	2	7	2	4	2	8
Compression	1	3	1	5	1	4	. . .	5
Shear	1	3	1	5	1	3	1	5
Bearing $e/D = 1.5$[(d)]	1	2	1	4	1	1	1	3
Bearing $e/D = 2.0$[(d)]	1	2	1	4	1	4	1	6
At room temperature								
Tension	12	12	12	36	18	17	18	53
Compression	3	3	3	9	2	4	3	9

Shear	3	3	3	9	3	4	2	9
Bearing *e*/*D* = 1.5[d]	3	3	3	9	3	3	3	9
Bearing *e*/*D* = 2.0[d]	3	3	3	9	3	3	3	9
Modulus of elasticity	1	1	. . .	2	1	1	. . .	2
At 150 °C (300 °F)								
Tension	1	3	1	5	2	4	2	8
Compression	1	1	1	3	1	4	. . .	5
Shear	1	1	1	3	1	3	1	5
Bearing *e*/*D* = 1.5[d]	1	1	1	3	1	2	1	4
Bearing *e*/*D* = 2.0[d]	. . .	. . .	. . .	0	1	4	1	6
At 260 °C (500 °F)								
Tension	2	3	2	7	. . .	. . .	. . .	0
Compression	1	3	1	5	. . .	. . .	. . .	0
Shear	1	3	1	5	. . .	. . .	. . .	0
Bearing *e*/*D* = 1.5[d]	1	2	1	4	. . .	. . .	. . .	0
Bearing *e*/*D* = 2.0[d]	2	2	1	5	. . .	. . .	. . .	0
Total number of tests	42	57	40	139	42	65	39	146

(a) L, longitudinal; LT, long transverse; ST, short transverse.

(b) Three heats.

(c) Four heats.

(d) *D*, hole diameter; *e*, edge distance measured from the hole center to the edge of the material in direction of applied stress

As shown in Table 1, test plans for mechanical properties include tension, compression, shear, and bearing strength tests; the effect of grain orientation is evaluated by testing specimens representative of the longitudinal, long-transverse, and short-transverse directions, as required. In addition to room-temperature tests, specimens are tested at -80, 150, and 260 °C (-110, 300, and 500 °F). The plan encompasses a total of 285 individual tests.

Ductility and the Amount of Forging Reduction. A principal objective of material control is to ensure that optimum mechanical properties will be obtained in the finished forging. The amount of reduction achieved in forging has a marked effect on ductility, as shown in Fig. 3, which compares ductility in the cast ingot, the wrought (rolled) bar or billet, and the forging. The curves in Fig. 3(a) indicate that when a wrought bar or billet is flat forged in a die, an increase in forging reduction does not affect longitudinal ductility, but does result in a gradual increase in transverse ductility. When a similar bar or billet is upset forged in a die, an increase in forging reduction results in a gradual decrease in axial ductility and a gradual increase in radial ductility.

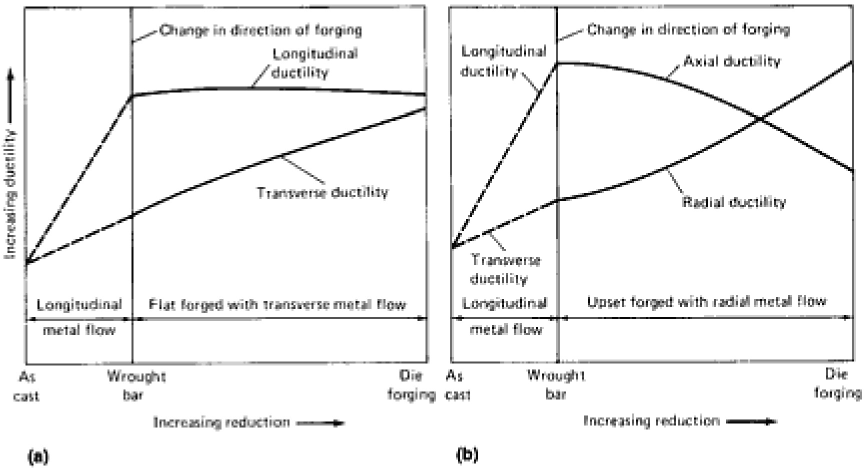


Fig. 3 Metal flow in forging. Effect of extent and direction of metal flow during forging on ductility. (a) Longitudinal and transverse ductility in flat-forged bars. (b) Axial and radial ductility in upset-forged bars

Grain Flow. Macroetching permits direct observation of grain direction and contour and also serves to detect folds, laps, and re-entrant flow. By macroetching of suitable specimens, grain flow can be examined in the longitudinal, long-transverse, and short-transverse directions. Macroetching also permits evaluation of complete sections, end to end and side to side, and a review of uniformity of macro grain size. Figure 4 illustrates grain flow in a representative forged part.

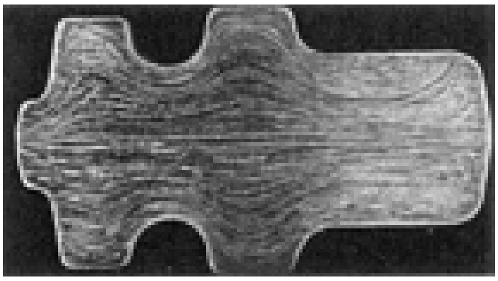


Fig. 4 Flow lines in a closed-die forging of AISI 4340 alloy steel. ~0.75×

End-Grain Exposure. Lowered resistance to stress-corrosion cracking in the long-transverse and short-transverse directions is related to end-grain exposure. A long, narrow test specimen sectioned so that the grain is parallel to the longitudinal axis of the specimen has no exposed end grain, except at the extreme ends, which are not subjected to loading. In contrast, a corresponding specimen cut in the transverse direction has end-grain exposure at all points along its length. End grain is especially pronounced in the short-transverse direction on die forgings designed with a flash line. Consequently, forged components designed to reduce or eliminate end grain have better resistance to stress-corrosion cracking.

Mechanical Properties

A major advantage of shaping metal parts by rolling, forging, or extrusion stems from the opportunities such processes offer the designer with respect to control of grain flow. The strength of these and similar wrought products is almost always greatest in the longitudinal direction (or equivalent) of grain flow, and the maximum load-carrying ability in the finished part is attained by providing a grain-flow pattern parallel to the direction of the major applied service loads when, in addition, sound, dense, good-quality metal of sufficiently fine grain size has been produced throughout.

Grain Flow and Anisotropy. Metal that is rolled, forged, or extruded develops and retains a fiber-like grain structure aligned in the principal direction of working. This characteristic becomes visible on external and sectional surfaces of wrought products when the surfaces are suitably prepared and etched. The "fibers" are the result of elongation of the microstructural constituents of the metal in the direction of working. Thus, the phrase "direction of grain flow" is commonly used to describe the dominant direction of these fibers within wrought metal products.

In wrought metal, the direction of grain flow is also evidenced by measurements of mechanical properties. Strength and ductility are almost always greater in the direction parallel to that of working. The characteristic of exhibiting different strength and ductility values with respect to the direction of working is referred to as "mechanical anisotropy" and is exploited in the design of wrought products.

Although best properties in wrought metals are most frequently the longitudinal (or equivalent), properties in other directions may yet be superior to those in products not wrought; that is, in cast ingots or in forging stock taken from only lightly worked ingot.

The square rolled section shown schematically in Fig. 5(a) is anisotropic with respect to average mechanical properties of test bars such as those shown in phantom. Average mechanical properties of the longitudinal bar 1 are superior to the average properties of the transverse bars 2 and 3. Mechanical properties are equivalent for bars 2 and 3 because the section is square, which implies equal reduction in section in both transverse directions.

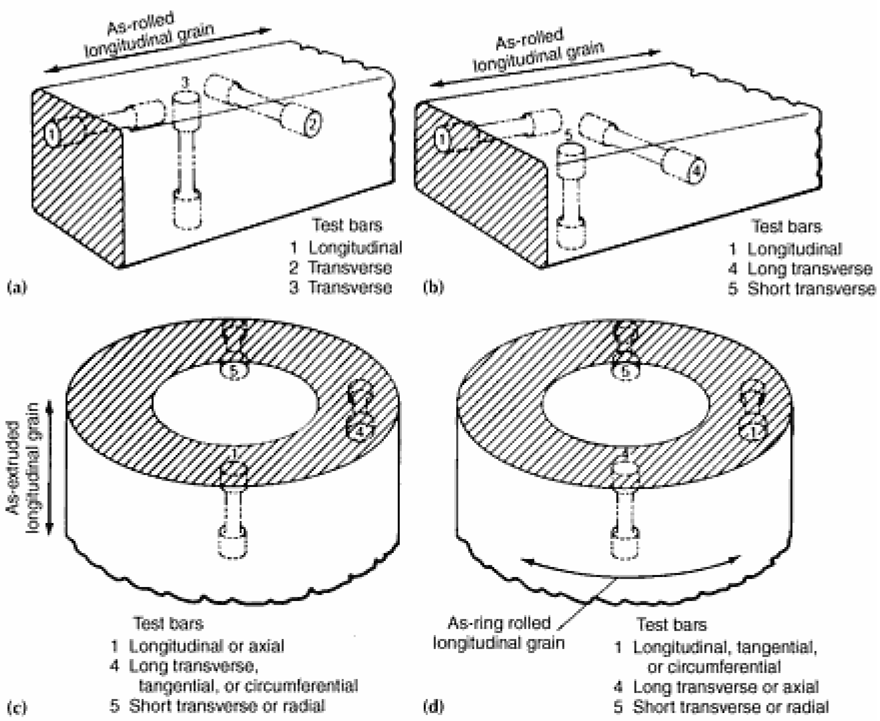

As-rolled longitudinal grain
1
2
3
Test bars
1 Longitudinal
2 Transverse
3 Transverse
(a)
As-rolled longitudinal grain
1
4
5
Test bars
1 Longitudinal
4 Long transverse
5 Short transverse
(b)
As-extruded longitudinal grain
Test bars
1 Longitudinal or axial
4 Long transverse, tangential, or circumferential
5 Short transverse or radial
(c)
As-ring rolled longitudinal grain
Test bars
1 Longitudinal, tangential, or circumferential
4 Long transverse or axial
5 Short transverse or radial
(d)

Fig. 5 Anisotropy and mechanical properties in forgings. Schematic views of sections from (a) square rolled stock, (b) rectangular rolled stock, (c) a cylindrical extruded section, and (d) a ring-rolled section, illustrating the effect of section configuration, forging process, or both, on the longitudinal direction in a forging

Mechanical anisotropy also is found in rectangular sections such as that shown in Fig. 5(b), in cylinders as in Fig. 5(c), and in rolled rings as in Fig. 5(d). Again, best strength properties are, on the average, those of the longitudinal, as in test bar 1. Flat rolling of a section such as that shown in Fig. 5(a) to a rectangular section (Fig. 5b) enhances the average "long transverse" properties of test bar 4 when compared with "short transverse" properties of test bar 5. Thus, such rectangular sections exhibit anisotropy among all three principal directions: longitudinal, long transverse, and short transverse. A design that employs a rectangular section such as that shown in Fig. 5(b) involves the properties in all these directions, not just the longitudinal. Thus, the longitudinal, long transverse, and short transverse service loads of rectangular sections are analyzed separately. The same concept can be applied to cylinders, whether extruded or rolled; longitudinal direction changes with the forging process used, as indicated in Fig. 5(c) and 5(d).

Fundamentals of Hammer and Press Forgings

Many small forgings are made in a die that has successive cavities to preshape the stock progressively into its final shape in the last, or "finish," cavity. Dies for large forgings are usually made to perform one operation at a time. The upper half of the die, having the deeper and more intricate cavity, is keyed or dovetailed into the hammer or press ram. The lower half is keyed to the "sow block" or bed of the hammer or press in precise alignment with the upper die. After being heated, the forging stock is placed in one cavity after another and is thus forged progressively to final shape.

The parting line is the plane along the periphery of the forging where the striking faces of the upper and lower dies come together. Usually, the die has a gutter or recess just outside of the parting line to receive overflow metal or flash forced out between the two dies in the finish cavity (Fig. 6). More complex forgings may have other parting lines around holes and other contours within the forging that may or may not be in the same plane as the outer parting line.

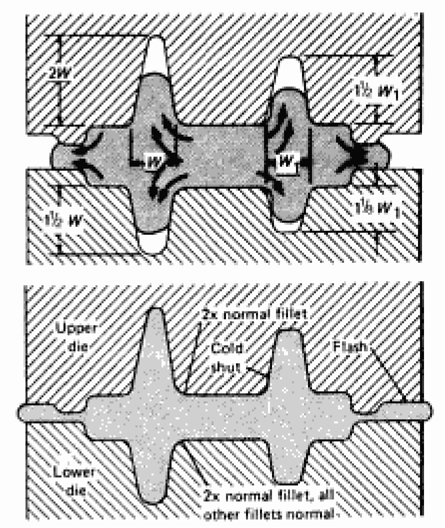

2W
1½ W₁
W
W₁
1½ W
1⅓ W₁
Upper die
2x normal fillet
Cold shut
Flash
Lower die
2x normal fillet, all other fillets normal

Fig. 6 Two stages of metal flow in forging. Top diagram shows limitation on height of ribs above and below the parting line.

For greatest economy, the outer parting line should be in a single plane. When it must be along a contour, either step or locked dies may be necessary to equalize thrust, as shown in Fig. 7. This may increase costs as much as 20%, because of the increased cost of dies and cost increases from processing difficulties in forging and trimming. Sharp steps or drops in the parting line should be limited to about 15° from the vertical in small parts and 25° in large forgings, to prevent a tearing instead of a cutting action in trimming off the flash. Locked dies may sometimes be avoided by locating the parting line as shown in the lower part of Fig. 8.

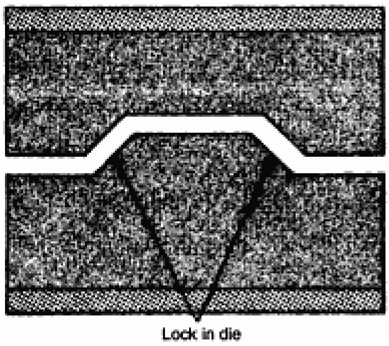
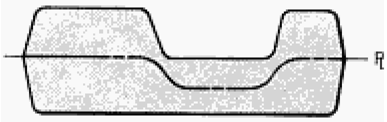
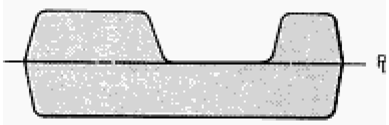


Fig. 7 Locked or stepped dies used to equalize thrust



Forged with lock in die



Forged without lock in die

Fig. 8 Orientation of a forging in the die to avoid counterlocked dies and to eliminate draft

Specification of optional parting lines on forgings to be made in different shops allows these lines to vary from shop to shop. Unless the draft has been removed, this variation may cause difficulties in locating forgings when they are being chucked for subsequent machining. However, shearing the draft is not always an adequate remedy if trimming angles vary. Forgings made in different shops are likely to be more consistent in quality and to have less variation in shape when a definite parting line is specified.

Draft on the sides of a forging is an angle or taper necessary for releasing the forging from the die and is desirable for long die life and economical production. Draft requirements vary with the shape and size of the forging. The effect of part size on the amount of metal needed for draft is illustrated by Fig. 9.

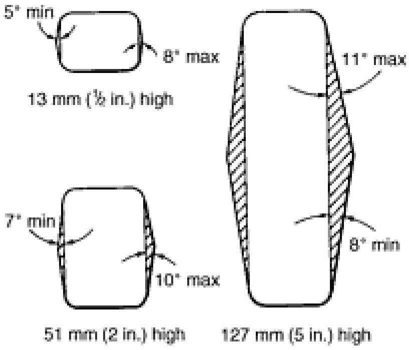


Fig. 9 Effect of part size on the amount of metal needed for draft in a forging

Inside draft is draft on surfaces that tightens on the die as the forging shrinks during cooling; examples are cavities such as narrow grooves or pockets. Outside draft is draft on surfaces such as ribs or bosses that shrink *away* from the die during cooling. Both are illustrated in Fig. 10, which shows inside draft to be greater than outside draft (the usual relation). Recommended draft angles and tolerances for steel forgings are given in Table 2.

Table 2 Draft angles and tolerances for steel forgings

Height or depth of draft		Commercial standard		Special standard	
mm	in.	Draft, degree	Tolerance[a], degree	Draft, degree	Tolerance[a], degree
Outside draft					
6.35-12.7	$\frac{1}{4}$-$\frac{1}{2}$	. . .	. . .	3	2
19-25	$\frac{3}{4}$-1	5	3	. . .	. . .
>12.75-25	>$\frac{1}{2}$-1	. . .	. . .	5	2

>25-76	>1-3	7	3	5	3
>76	>3	7	4	7	3
Inside draft					
6.35-25.4	$\frac{1}{4}$-1	7	3	5	3
>25.4	>1	10	3	10	3

(a) The minus tolerance is zero.

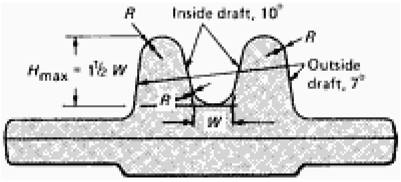
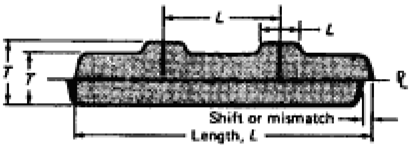


Fig. 10 Definition of inside and outside draft and limitations on the depth of the cavities between ribs.

Tolerances

Forging tolerances, based on area and weight, that represent good commercial practice are listed in Tables 3 and 4. These tolerances apply to the dimensions shown in the illustration accompanying Table 3. In using these tables to determine the size of the forging, the related tolerances, such as mismatch, die wear, and length, should be added to allowance for machining plus machined dimensions. On the average, tolerances listed in Tables 3 and 4 conform to the full process tolerances of actual production parts and yield more than 99% acceptance of any dimension specified from this table. In particular, instances may be found of precise accuracy or rarely as much as ±50% error in the tolerances recommended in Table 4.

Table 3 Recommended commercial tolerances on length and location



Maximum length of forging		Tolerance on length or location	
mm	**in.**	**mm**	in.
150	6	+1.19, -0.79	**+0.047, -0.031**
380	15	+1.57, -1.19	**+0.062, -0.047**

610	24	+3.18, -1.57	**+0.125, -0.062**
910	36	+3.18, -1.57	**+0.125, -0.062**
1220	48	+3.18, -3.18	**+0.125, -0.125**
1520	60	+4.75, -3.18	**+0.187, -0.125**
1830	**72**	**+5.56, -3.18**	**+0.219, -0.125**

Table 4 Recommended commercial tolerances for steel forgings

Forging size				Tolerance							
				Thickness(a)				**Mismatch(a), plus**		Die wear, plus	
Area		**Weight**		**Plus**		**Minus**					
10^3 mm^2	**in.^{2}**	**kg**	**lb**	**mm**	**in.**	**mm**	**in.**	**mm**	**in.**	**mm**	in.
3.2	5.0	0.45	1	0.79	0.031	0.41	0.016	0.41 to 0.79	0.016 to 0.031	0.79	**0.031**
4.5	7.0	3.2	7	1.57	0.062	0.79	0.031	0.41 to 0.79	0.016 to 0.031	1.57	**0.062**
6.5	10.0	0.7	1.5	0.79	0.031	0.79	0.031	0.41 to 0.79	0.016 to 0.031	0.79	**0.031**
7.7	12.0	5.5	12	1.57	0.062	0.79	0.031	0.41 to 0.79	0.016 to 0.031	1.57	**0.062**
12.9	20.0	0.9	2	1.57	0.062	0.79	0.031	0.41 to 0.79	0.016 to 0.031	1.57	**0.062**
12.9	20.0	14	30	1.57	0.062	0.79	0.031	0.51 to 1.02	0.020 to 0.040	1.57	**0.062**
24.5	38.0	2	4.5	1.57	0.62	0.79	0.031	0.41 to 0.79	0.016 to 0.031	1.57	**0.062**
24.5	38.0	36	80	1.57	0.62	0.79	0.031	0.64 to 1.27	0.025 to 0.050	1.57	**0.062**
32.3	50.0	3	8	1.57	0.062	0.79	0.031	0.51 to 1.02	0.020 to 0.040	1.57	**0.062**
32.3	50.0	27	60	1.57	0.062	0.79	0.031	0.51 to 1.02	0.020 to 0.040	1.57	**0.062**
32.3	50.0	45	100	1.57	0.062	0.79	0.031	0.64 to 1.27	0.025 to 0.050	1.57	**0.062**

61.3	95.0	5	11	1.57	0.062	0.079	0.031	0.51 to 1.02	0.020 to 0.040	1.57	**0.062**
85.2	132.0	8	17	1.57	0.062	0.79	0.031	0.64 to 1.27	0.025 to 0.050	1.57	**0.062**
107	166.0	33	73	2.39	0.094	0.79	0.031	0.76 to 1.52	0.030 to 0.060	2.39	**0.094**
113	175.0	68	150	2.39	0.094	0.79	0.031	0.76 to 1.52	0.030 to 0.060	2.39	**0.094**
130	201.0	18	40	1.57	0.062	0.79	0.031	0.64 to 1.27	0.025 to 0.050	1.57	**0.062**
155	240.0	23	51.5	2.39	0.094	0.79	0.031	0.76 to 1.52	0.030 to 0.060	2.39	**0.094**
161	250.0	114	250	2.39	0.094	0.79	0.031	0.76 to 1.52	0.030 to 0.060	2.39	**0.094**
171	265.0	27	60	2.39	0.094	0.79	0.031	0.76 to 1.52	0.030 to 0.060	2.39	**0.094**
177	275.0	30	65	3.18	0.125	0.79	0.031	1.19 to 2.39	0.047 to 0.094	3.18	**0.125**
194	300.0	34	75	3.18	0.125	1.57	0.062	1.19 to 2.39	0.047 to 0.094	3.18	**0.125**
194	300.0	159	350	2.39	0.094	0.79	0.031	0.76 to 1.52	0.030 to 0.060	2.39	**0.094**
242	375.0	205	450	3.18	0.125	0.79	0.031	1.19 to 2.39	0.047 to 0.094	3.18	**0.125**
268	415.0	139	306	3.18	0.125	1.57	0.062	1.19 to 2.39	0.047 to 0.094	3.18	**0.125**
339	525.0	340	750	3.18	0.125	1.57	0.062	1.19 to 2.39	0.047 to 0.094	3.18	**0.125**
580	**900.0**	**455**	**1000**	**3.18**	**0.125**	**1.57**	**0.062**	**1.19 to 2.39**	**0.047 to 0.094**	**3.18**	**0.125**

(a) The illustration in Table 3 shows locations of thickness and mismatch.

The characteristics of die wear are shown graphically in Fig. 11. The part represented was made of 4140 steel, using ten blows in a 11 kN (2500 lbf) board hammer. Tolerances were commercial standard, and the part was later coined to a thickness tolerance of +0.25 mm, -0.000 (+0.010 in., -0.000). The die block, 250 by 455 by 455 mm (10 by 18 by 18 in.), was hardened to 42 HRC. After 30,000 forgings had been produced, the die wore as indicated and the dies were resunk.

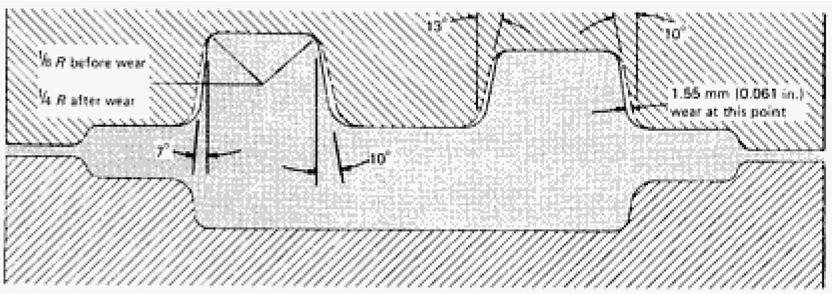

13°
10°
1/8 R before wear
1/4 R after wear
1.55 mm (0.061 in.) wear at this point
7°
10°

Fig. 11 Extent of die wear in a die block hardened to 42 HRC. The block was evaluated for die wear after producing 30,000 forgings of 4140 steel at a rate of 10 blows/workpiece with an 11 kN (2500 lbf) hammer.

Ranges of mismatch tolerance are given in Table 4. The higher values are to be added to tolerances for forgings that need locked dies or involve side thrust on the dies during forging. On forgings heavier than 23 kg (50 lb), it is sometimes necessary to grind out mismatch defects up to 3.18 mm ($\frac{1}{8}$ in.) maximum.

Flash is trimmed in a press with a trimming die shaped to suit the plan view, outline, and side view contour of the parting line. The forging may be trimmed with a stated amount of burr or flash left around the periphery at the parting line.

Design of Hot Upset Forgings

Hot heading, upset forging, or more broadly, machine forging consists primarily of holding a bar of uniform cross section, usually round, between grooved dies and applying pressure on the end in the direction of the axis of the bar by using a heading tool so as to upset or enlarge the end into an impression of the die. The shapes generally produced include a variety of enlargements of the shank, or multiple enlargements of the shank and "re-entrant angle" configurations. Transmission cluster gears, pinion blanks, shell bodies and many other shaped parts are adapted to production by the upset machine forging process. This process produces a "looped" grain flow of major importance for gear teeth. Simple, headed forgings may be completed in one step, while some that have large, configured heads or multiple upsets may require as many as six steps. Upset forgings are produced weighing from less than 0.45 kg (1 lb) to about 225 kg (500 lb).

Machining Stock Allowances. The standard for machining stock allowance on any upset portion of the forging is 2.39 mm (0.094 in.), although allowances vary from 1.58 to 3.18 mm (0.062 to 0.125 in.), depending on size of upset, material and shape of the part (Fig. 12a).

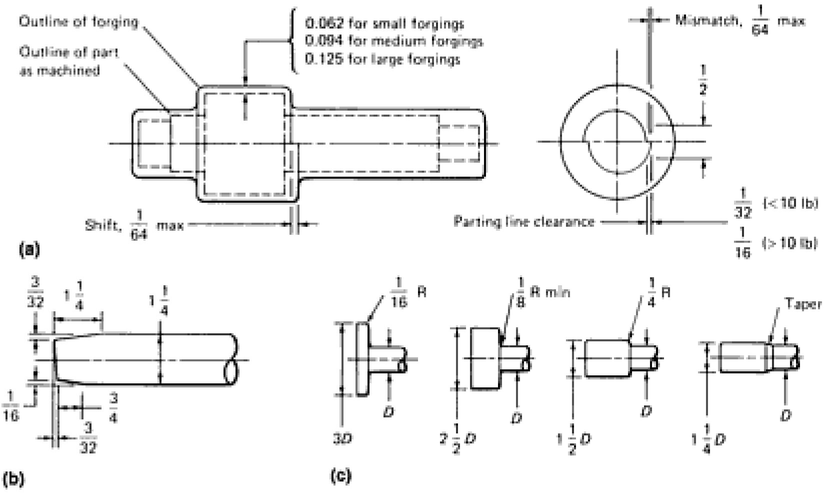

Outline of forging
Outline of part as machined
0.062 for small forgings
0.094 for medium forgings
0.125 for large forgings
Mismatch, 1/64 max
1/2
Shift, 1/64 max
Parting line clearance
1/32 (< 10 lb)
1/16 (> 10 lb)
(a)
3/32
1 1/4
1 1/4
1/16
3/4
3/32
(b)
1/16 R
1/8 R min
1/4 R
Taper
D
D
D
D
3D
2 1/2 D
1 1/2 D
1 1/4 D
(c)

Fig. 12 Machining stock allowances for hot upset forgings. (a) Hot upset forging terminology and standards. (b) Probable shape of shear-cut ends. (c) Variation of corner radius with thickness of upset. These parts are the

simplest forms of upset forgings. Dimensions given in inches

Mismatch and shift of dies are each limited to 0.406 mm (0.016 in.) maximum. Mismatch is the location of the gripper dies with respect to each other.

Parting-line clearance is required in gripper dies for tangential clearance in order to avoid undercut and difficulty in removal of the forging from the dies (Fig. 12a).

Tolerances for shear-cut ends have not been established. Figure 12(b) shows a shear-cut end on a 31.8 mm ($1\frac{1}{4}$ in.) diameter shank. Straight ends may be produced by torch cutting, hack-sawing, or abrasive wheel cutoff, at a higher cost than that of shearing.

Corner radii should follow the contours of the finished part, with a minimum radius of 1.59 mm ($\frac{1}{16}$ in.). Radii at the outer diameter of the upset face are not required, but may be specified as desired. Variations in thickness of the upset require variations in radii, as shown in Fig. 12(c), because the source of the force is farther removed and the die cavity is more difficult to fill. When a long upset is only slightly larger than the original bar size, a taper is advisable instead of a radius.

Tolerances for all upset forged diameters are generally +1.59 mm, -0 (+$\frac{1}{16}$ in., -0) except for thin sections of flanges and upsets relatively large in ratio to the stock sizes used, where they are +2.38 mm, -0 (+$\frac{3}{32}$ in., -0). The increase of tolerances over the standard +1.59 mm, -0 is sometimes a necessity, because of variations in size of hot rolled mill bars, extreme die wear, or complexity of the part.

Draft angles may vary from 1 to 7°, depending on the characteristics of the forging design. Draft is needed to release the forging from the split dies; it also reduces the shearing of face surfaces in transfer from impression to impression.

For an upset forged part that requires several operations or passes, the dimensioning of lengths is determined on the basis of the design of each individual pass or operation.

STEEL CASTINGS

Introduction

STEEL CASTINGS can be made from any of the many types of carbon and alloy steel produced in wrought form. Such castings are produced by pouring molten steel of the desired composition into a mold of the desired configuration and allowing the steel to solidify. The mold material may be silica, zircon, chromite or olivine sand, graphite, metal, or ceramic. Choice of mold material depends on the size, intricacy, and dimensional accuracy of the casting and on cost. While the producible size, surface finish, and dimensional accuracy of castings vary widely with the type of mold, the properties of the cast steel are not affected significantly. Steel castings produced in any of the various types of molds and wrought steel of equivalent chemical composition respond similarly to heat treatment, have the same weldability, and have similar physical, mechanical, and corrosion properties. Cast steels do not exhibit the effects of directionality on mechanical properties that are typical of wrought steels.

Table 1 Summary of specification requirements for various carbon steel castings

Unless otherwise noted, all the grades listed in this table are restricted to a phosphorus content of 0.040% max and a sulfur content of 0.045% max.

Class or grade	**Tensile strength[a]**		**Yield strength[a]**		**Minimum elongation in 50 mm (2 in.), %**	**Minimum reduction in area, %**	**Chemical composition[b], %**			**Other requirements**	Condition or specific applications
	MPa	**ksi**	**MPa**	**ksi**			**C**	**Mn**	**Si**		
ASTM A 27: carbon steel castings for general applications											
N-1	. . .	. . .	. . .	. . .	. . .	. . .	0.25[c]	0.75[c]	0.80	0.06% S, 0.05% P	**Chemical analysis only**
N-2	. . .	. . .	. . .	. . .	. . .	. . .	0.35[c]	0.60[c]	0.80	0.06% S, 0.05% P	**Heat treated but not mechanically tested**
U60-30	415	60	205	30	22	30	0.25[c]	0.75[c]	0.80	0.06% S, 0.05% P	**Mechanically tested but not heat treated**
60-30	415	60	205	30	24	35	0.30[c]	0.60[c]	0.80	0.06% S, 0.05% P	**Heat treated and mechanically tested**
65-35	450	65	240	35	24	35	0.30[c]	0.70[c]	0.80	0.06% S, 0.05% P	**Heat treated and mechanically tested**
70-36	485	70	250	36	22	30	0.35[c]	0.70[c]	0.80	0.06% S, 0.05% P	**Heat treated and mechanically tested**
70-40	485	70	275	40	22	30	0.25[c]	1.20[c]	0.80	0.06% S, 0.05% P	**Heat treated and mechanically tested**
ASTM A 148: carbon steel castings for structural applications[d]											
80-40	550	80	275	40	18	30	[e]	[e]	[e]	0.06% S, 0.05% P	**Composition and heat treatment necessary to achieve specified mechanical properties**
80-50	550	80	345	50	22	35	[e]	[e]	[e]	0.06% S, 0.05% P	**Composition and heat treatment necessary to achieve specified mechanical properties**
90-60	620	90	415	60	20	40	[e]	[e]	[e]	0.06% S, 0.05% P	**Composition and heat treatment necessary to achieve specified mechanical properties**

105-85	725	105	585	85	17	35	(e)	(e)	(e)	0.06% S, 0.05% P	**Composition and heat treatment necessary to achieve specified mechanical properties**
SAE J435c: see Table 2 for alloy steel castings specified in SAE J435c											
0022	. . .	. . .	. . .	. . .	. . .	. . .	0.12-0.22	0.50-0.90	0.60	187 HB max	**Low-carbon steel suitable for carburizing**
0025	415	60	207	30	22	30	0.25(c)	0.75(c)	0.80	187 HB max	**Carbon steel welding grade**
0030	450	65	241	35	24	35	0.30(c)	0.70(c)	0.80	131-187 HB	**Carbon steel welding grade**
0050A	585	85	310	45	16	24	0.40-0.50	0.50-0.90	0.80	170-229 HB	**Carbon steel medium-strength grade**
0050B	690	100	485	70	10	15	0.40-0.50	0.50-0.90	0.80	207-255 HB	**Carbon steel medium-strength grade**
080	550	80	345	50	22	35	. . .	. . .	. . .	163-207 HB	**Medium-strength low-alloy steel**
090	620	90	415	60	20	40	. . .	. . .	. . .	187-241 HB	**Medium-strength low-alloy steel**
HA, HB, HC(f)	. . .	. . .	. . .	. . .	. . .	. . .	0.25-0.34	(f)	(f)	See Fig. 1	**Hardenability grades (Fig. 1)**
ASTM A 216: carbon steel castings suitable for fusion welding and high-temperature service											
WCA	415-585	60-85	205	30	24	35	0.25	0.70(c)	0.60	(g)	**Pressure-containing parts**
WCB	485-655	70-95	250	36	22	35	0.30	1.00(c)	0.60	(g)	**Pressure-containing parts**
WCC	485-655	70-95	275	40	22	35	0.25	1.20(c)	0.50	(g)	**Pressure-containing parts**
Other ASTM cast steel specifications with carbon steel grades(h)											
A 352-LCA	415-585	60-85	205	30	24	35	0.25	0.70(c)	0.60	(g)(i)(j)	**Low-temperature applications**

A 352-LCB	450-620	65-90	240	35	24	35	0.30	1.00	0.60	(g)(j)(k)	**Low-temperature applications**
A 356-grade 1	485	70	250	36	20	35	0.35	0.70(c)	0.60	0.035% P max, 0.030% S max	**Castings for valve chests, throttle valves, and other heavy-walled components for steam turbines**
A 757-A1Q	**450**	**65**	**240**	**35**	**24**	**35**	**0.30**	**1.00**	**0.60**	**(j)(k)(l)**	**Castings for pressure-containing applications at low temperatures**

(a) Where a single value is shown, it is a minimum.

(b) Where a single value is shown, it is a maximum.

(c) For each reduction of 0.01% C below the maximum specified, an increase of 0.04% Mn above the maximum specified is permitted up to the maximums given in the applicable ASTM specifications.

(d) Grades may also include low-alloy steels; see Table 2 for the stronger grades of ASTM A 148.

(e) Unless specified by purchaser, the compositions of cast steels in ASTM A 148 are selected by the producer in order to achieve the specified mechanical properties.

(f) Purchased on the basis of hardenability, with manganese and other elements added as required.

(g) Specified residual elements include 0.30% Cu max, 0.50% Ni max, 0.50% Cr max, 0.20% Mo max, and 0.03% V max, with the total residual elements not exceeding 1.00%.

(h) These ASTM specifications also include alloy steel castings for the general type of applications listed in the table.

(i) Testing temperature of -32 °C (-25 °F).

(j) Charpy V-notch impact testing at the specified test temperature with an energy value of 18 J (13 ft · lbf) min for two specimens and an average of three.

(k) Testing temperature of -46 °C (-50 °F).

(l) Specified residual elements of 0.03% V, 0.50% Cu, 0.50% Ni, 0.40% Cr, and 0.25% Mo, with total amount not exceeding 1.00%. Sulfur and phosphorus content, each 0.025% max

The steel castings discussed in this article are classified into four general groups according to their carbon or alloy contents. Carbon steel castings account for three of these groups: low-carbon steel castings with less than 0.20% carbon, medium-carbon castings with 0.20 to 0.50% carbon, and high-carbon castings with more than 0.50% carbon. The fourth group, low-alloy steel castings, is generally limited to grades with a total alloy content of less than 8%.

Specifications

Steel castings are usually purchased to meet specified mechanical properties, with some restrictions on chemical composition. Tables 1 and 2 list the requirements given in various ASTM specifications and in SAE J435c. Table 1 lists primarily carbon steel castings (with some comparable low-alloy types), while Table 2 lists several low-alloy cast steels and some cast steels with chromium content up to 10.0%.

Table 2 Summary of specification requirements for various alloy steel castings with chromium contents up to 10%

Material class[a]	**Tensile strength**[b]		**Yield strength**[b]		**Minimum elongation in 50 mm (2 in.), %**	**Minimum reduction in area, %**	Composition[c], %						
	MPa	**ksi**	**MPa**	**ksi**			**C**	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	Other
ASTM A 148: steel castings for structural applications[d]													
115-95	795	115	655	95	14	30	. . .	. . .	. . .	. . .	. . .	. . .	[e]
135-125	930	135	860	125	9	22	. . .	. . .	. . .	. . .	. . .	. . .	[e]
150-135	1035	150	930	135	7	18	. . .	. . .	. . .	. . .	. . .	. . .	[e]
160-145	1105	160	1000	145	6	12	. . .	. . .	. . .	. . .	. . .	. . .	[e]
165-150	1140	165	1035	150	5	20	. . .	. . .	. . .	. . .	. . .	. . .	[f]
165-150L	1140	165	1035	150	5	20	. . .	. . .	. . .	. . .	. . .	. . .	[f]
210-180	1450	210	1240	180	4	15	. . .	. . .	. . .	. . .	. . .	. . .	[f]
210-180L	1450	210	1240	180	4	15	. . .	. . .	. . .	. . .	. . .	. . .	[f]
260-210	1795	260	1450	210	3	6	. . .	. . .	. . .	. . .	. . .	. . .	[f]
260-210L	1795	260	1450	210	3	6	. . .	. . .	. . .	. . .	. . .	. . .	[f]
SAE J435c: see Table 1 for the carbon steel castings specified in SAEJ435c[g]													
0105	725	105	586	85	17	35	. . .	. . .	. . .	. . .	. . .	. . .	[h]
0120	827	120	655	95	14	30	. . .	. . .	. . .	. . .	. . .	. . .	[h]

0150	1035	150	862	125	9	22	. . .	. . .	. . .	. . .	. . .	. . .	(h)
0175	1207	175	1000	145	6	12	. . .	. . .	. . .	. . .	. . .	. . .	(h)
ASTM A 217: alloy steel castings for pressure-containing parts and high-temperature service													
WC1	450-620	65-90	240	35	24	35	0.25	0.50-0.80	0.60	0.35(i)	0.50(i)	0.45-0.65	(i)(j)
WC4	485-655	70-95	275	40	20	35	0.20	0.50-0.80	0.60	0.50-0.80	0.70-1.10	0.45-0.65	(j)(k)
WC5	485-655	70-95	275	40	20	35	0.20	0.40-0.70	0.60	0.50-0.90	0.60-1.00	0.90-1.20	(j)(k)
WC6	485-655	70-95	275	40	20	35	0.20	0.50-0.80	0.60	1.00-1.50	0.50(i)	0.45-0.65	(i)(j)
WC9	485-655	70-95	275	40	20	35	0.18	0.40-0.70	0.60	2.00-2.75	0.50(i)	0.9-1.20	(i)(j)
WC11	550-725	80-105	345	50	18	45	0.15-0.21	0.50-0.80	0.30-0.60	1.00-1.75	0.50(i)	0.45-0.65	(i)(l)
C5	620-795	90-115	415	60	18	35	0.20	0.40-0.70	0.75	4.00-6.50	0.50(i)	0.45-0.65	(i)(j)
C12	620-795	90-115	415	60	18	35	0.20	0.35-0.65	1.00	8.00-10.00	0.50(i)	0.90-1.20	(i)(j)
ASTM A 389: alloy steel castings (NT) suitable for fusion welding and pressure-containing parts at high temperatures													
C23	485	70	275	40	18	35	0.20	0.30-0.80	0.60	1.00-1.50	. . .	0.45-0.65	(h)(m)
C24	550	80	345	50	15	35	0.20	0.30-0.80	0.60	1.00-1.25	. . .	0.90-1.20	(h)(m)
ASTM A 487: alloy steel castings (NT or QT) for pressure-containing parts at high temperatures													
1A (NT)	585-760	85-110	380	55	22	40	0.30	1.00	0.80	0.35(n)	0.50(n)	0.25(n)(o)	**0.5 Cu(h)(n)**
2B (QT)	620-795	90-115	450	65	22	45	0.30	1.00	0.80	0.35(n)	0.50(n)	0.25(n)(o)	**0.5 Cu(h)(n)**

1C (NT or QT)	620	90	450	65	22	45	0.30	1.00	0.80	0.35(n)	0.50(n)	0.25(n)(o)	**0.5 Cu(h)(n)**
2A (NT)	585-760	85-110	365	53	22	35	0.30	1.10-1.40	0.80	0.35(i)	0.50(i)	0.10-0.30	(i)(p)
2B (QT)	620-795	90-115	450	65	22	40	0.30	1.10-1.40	0.80	0.35(i)	0.50(i)	0.10-0.30	(i)(p)
2C (NT or QT)	620	90	450	65	22	40	0.30	1.10-1.40	0.80	0.35(i)	0.50(i)	0.10-0.30	(i)(p)
4A (NT or QT)	620-795	90-115	415	60	20	40	0.30	1.00	0.80	0.40-0.80	0.40-0.80	0.15-0.30	(k)(p)
4B (QT)	725-895	105-130	585	85	17	35	0.30	1.00	0.80	0.40-0.80	0.40-0.80	0.15-0.30	(k)(p)
4C (NT or QT)	620	90	415	60	20	40	0.30	1.00	0.80	0.40-0.80	0.40-0.80	0.15-0.30	(k)(p)
4D (QT)	690	100	515	75	17	35	0.30	1.00	0.80	0.40-0.80	0.40-0.80	0.15-0.30	(k)(p)
4E (QT)	795	115	655	95	15	35	0.30	1.00	0.80	0.40-0.80	0.40-0.80	0.15-0.30	(k)(p)
6A (NT)	795	115	550	80	18	30	0.38	1.30-1.70	0.80	0.40-0.80	0.40-0.80	0.30-0.40	(k)(p)
6B (QT)	825	120	655	95	15	35	0.38	1.30-1.70	0.80	0.40-0.80	0.40-0.80	0.30-0.40	(k)(p)
7A (QT)(q)	795	115	690	100	15	30	0.20	0.60-1.00	0.80	0.40-0.80	0.70-1.00	0.40-0.60	(k)(p)(r)
8A (NT)	585-760	85-110	380	55	20	35	0.20	0.50-0.90	0.80	2.00-2.75	. . .	0.90-1.10	(k)(p)
8B (QT)	725	105	585	85	17	30	0.20	0.50-0.90	0.80	2.00-2.75	. . .	0.90-1.10	(k)(p)
8C (QT)	690	100	515	75	17	35	0.20	0.50-0.90	0.80	2.00-2.75	. . .	0.90-1.10	(k)(p)
9A (NT or QT)	620	90	415	60	18	35	0.33	0.60-1.00	0.80	0.75-1.10	0.50(i)	0.15-0.30	(i)(p)

9B (QT)	725	105	585	85	16	35	0.33	0.60-1.00	0.80	0.75-1.10	0.50(i)	0.15-0.30	(i)(p)
9C (NT or QT)	620	90	415	60	18	35	**Composition same as 9A (NT or QT) but with a slightly higher tempering temperature**						
9D (QT)	690	100	515	75	17	35	0.33	0.60-1.00	0.80	0.75-1.10	0.50(i)	0.15-0.30	(i)(p)
10A (NT)	690	100	485	70	18	35	0.30	0.60-1.00	0.80	0.55-0.90	1.40-2.00	0.20-0.40	(k)(p)
10B (QT)	860	125	690	100	15	35	0.30	0.60-1.00	0.80	0.55-0.90	1.40-2.00	0.20-0.40	(k)(p)
11A (NT)	485-655	70-95	275	40	20	35	0.20	0.50-0.80	0.60	0.50-0.80	0.70-1.10	0.45-0.65	(p)(s)
11B (QT)	725-895	105-130	585	85	17	35	0.20	0.50-0.80	0.60	0.50-0.80	0.70-1.10	0.45-0.65	(p)(s)
12A (NT)	485-655	70-95	275	40	20	35	0.20	0.40-0.70	0.60	0.50-0.90	0.60-1.00	0.90-1.20	(p)(s)
12B (QT)	725-895	105-130	585	85	17	35	0.20	0.40-0.70	0.60	0.50-0.90	0.60-1.00	0.90-1.20	(p)(s)
13A (NT)	620-795	90-115	415	60	18	35	0.30	0.80-1.10	0.60	0.40(t)	1.40-1.75	0.20-0.30	(p)(t)
13B (QT)	725-895	105-130	585	85	17	35	0.30	0.80-1.10	0.60	0.40(t)	1.40-1.75	0.20-0.30	(p)(t)
14A (QT)	825-1000	120-145	655	95	14	30	0.55	0.80-1.10	0.60	0.40(t)	1.40-1.75	0.20-0.30	(p)(t)
16A (NT)(u)	**485-655**	**70-95**	**275**	**40**	**22**	**35**	**0.12(v)**	**2.10(v)**	**0.50**	**0.20(s)**	**1.00-1.40**	**0.10(s)**	**(s)(w)**

(a) NT, normalized and tempered; QT, quenched and tempered.

(b) When a single value is shown, it is a minimum.

(c) When a single value is shown, it is a maximum.

(d) Unless specified by the purchaser, the compositions of cast steels in ASTM A 148 are selected by the producer and therefore may include either carbon or alloy steels; see Table 1 for the lower-grade steels specified in ASTM A 148.

(e) 0.06% S (max), 0.05% P (max).

(f) 0.020% S (max), 0.020% P (max).

(g) Similar to the cast steel in ASTM A 148.

(h) 0.045% S (max), 0.040% P (max).

(i) When residual maximums are specified for copper, nickel, chromium, tungsten, and vanadium, their total content shall not exceed 1.00%.

(j) 0.50% Cu (max), 0.10% W (max), 0.045% S (max), 0.04% P (max).

(k) When residual maximums are specified for copper, nickel, chromium, tungsten, and vanadium, their total residual content shall not exceed 0.60%.

(l) 0.35% Cu (max), 0.03% V (max), 0.015% S (max), 0.020% P (max).

(m) 0.15-0.25% V.

(n) The specified residuals of copper, nickel, chromium, and molybdenum (plus tungsten), shall not exceed a total content of 1.00%.

(o) Includes the residual content of tungsten.

(p) 0.50% Cu (max), 0.10% W (max), 0.03% V (max), 0.045% S (max), 0.04% P (max).

(q) Material class 7A is a proprietary steel and has a maximum thickness of 63.5 mm ($2\frac{1}{2}$ in.).

(r) Specified elements include 0.15-0.50% Cu, 0.03-0.10% V, and 0.002-0.006% B.

(s) When residual maximums are specified for copper, nickel, chromium, tungsten, molybdenum, and vanadium, their total content shall not exceed 0.50%.

(t) When residual maximums are specified for copper, nickel, chromium, tungsten, and vanadium, their total content shall not exceed 0.75%.

(u) Low-carbon grade with double austenitization.

(v) For each reduction of 0.01% C below the maximum, an increase of 0.04% Mn is permitted up to a maximum of 2.30%.

(w) 0.20% Cu (max), 0.10% W (max), 0.02% V (max), 0.02% S (max), 0.02% P (max)

In the low-strength ranges, some specifications limit carbon and manganese content, usually to ensure satisfactory weldability. In SAE J435c, carbon and manganese are specified to ensure that the minimum desired hardness and strength are obtained after heat treatment. For special applications, other elements may be specified either as maximum or minimum, depending on the characteristics desired.

If only mechanical properties are specified, the chemical composition of castings for general engineering applications is usually left to the discretion of the casting supplier. For specific applications, however, certain chemical compositions limits have been established to ensure the development of specified mechanical properties after proper heat treatment, as well as to facilitate welding, uniform response to heat treatment, or other requirements. Hardness is specified for most grades of SAE J435c to ensure machinability, ease of inspection for high production rate items, or certain characteristics pertaining to wear.

SAE J435c includes three grades, HA, HB, and HC, with specified hardenability requirements. Figure 1 plots hardenability requirements, both minimum and maximum, for these steels. Hardenability is determined by the end-quench hardenability test described in the article "Hardenability of Steels" in this Section. Other specifications require minimum hardness at one or two locations on the end-quench specimen. In general, hardenability is specified to ensure a predetermined degree of transformation from austenite to martensite during quenching, in the thickness required. This is important in critical parts requiring toughness and optimal resistance to fatigue.

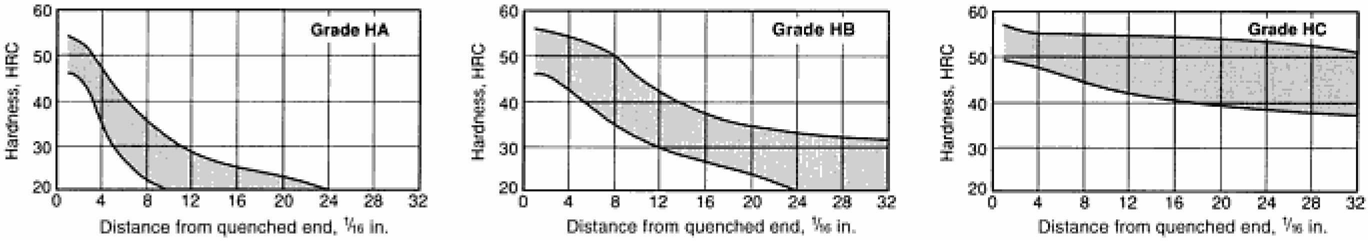


Fig. 1 End-quench hardenability limits for the hardenability grades of cast steel specified in SAE J435c. The nominal carbon content of these steels is 0.30% C (see Table 1). Manganese and other alloying elements are added as required to produce castings that meet these limits.

Particularly when the purchaser heat treats a part after other processing, a casting will be ordered to compositional limits closely equivalent to the SAE-AISI wrought steel compositions, with somewhat higher silicon permitted. As in other steel castings, it is best not to specify a range of silicon, but to permit the foundry to use the silicon and manganese combination needed to achieve required soundness in the shape being cast. The silicon content is frequently higher in cast steels than for the same nominal composition in wrought steel. A silicon content higher than 0.80% is considered an alloy addition because it contributes significantly to resistance to tempering.

Mechanical Properties

General Characteristics. Figure 2 shows the basic trends of the mechanical properties of cast carbon steels as a function of carbon content for four different heat treatments. For a given heat treatment, a higher carbon content generally results in higher hardness and strength levels with lower ductility and toughness values. Because yield strength is a primary design criterion for structural applications, Fig. 3 plots tensile strength, ductility (as measured by elongation), and toughness (based on Charpy V-notch impact energy) versus yield strength for low-alloy cast steels.

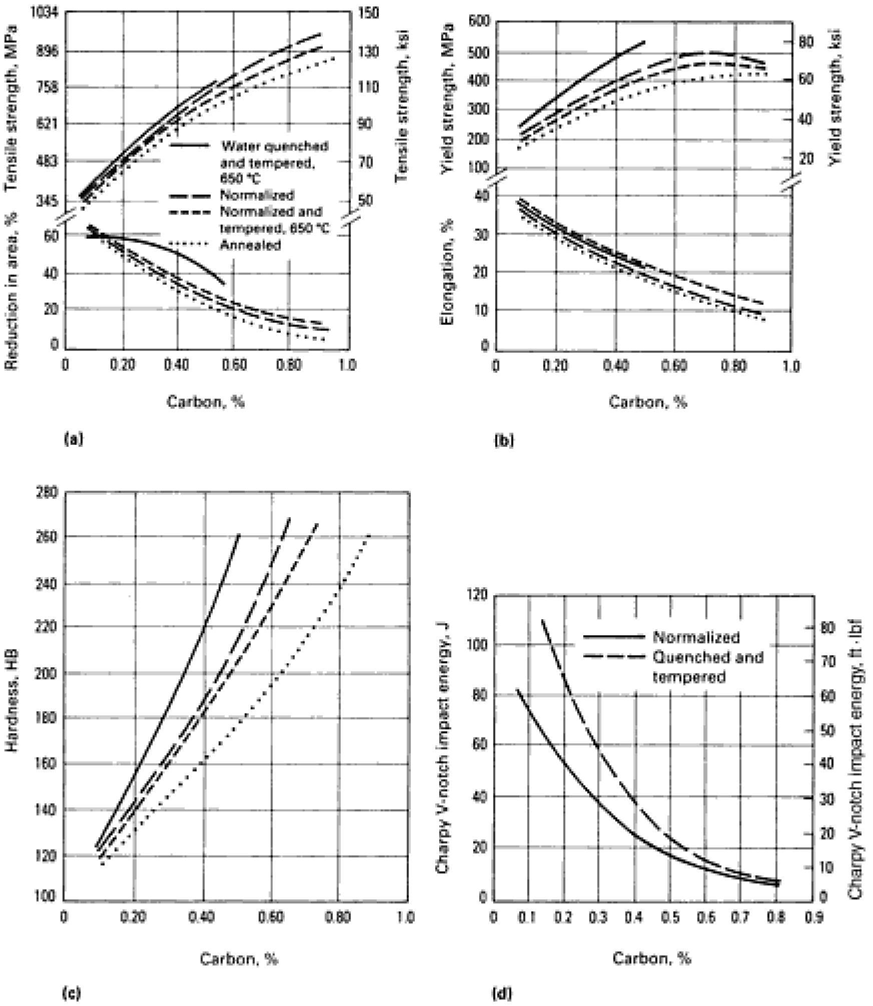


Fig. 2 Properties of cast carbon steels as a function of carbon content and heat treatment. (a) Tensile strength and reduction of area. (b) Yield strength and elongation. (c) Brinell hardness. (d) Charpy V-notch impact energy

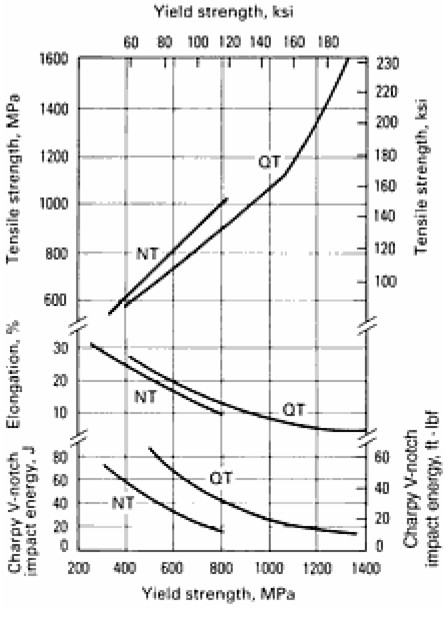


Fig. 3 Room-temperature properties of cast low-alloy steels. QT, quenched and tempered; NT, normalized and

tempered

Tensile and Yield Strengths. If ferritic steels are compared at a given level of hardness and hardenability, the tensile and yield strengths of cast, rolled, forged, and welded metal are virtually identical, regardless of alloy content. Consequently, where tensile and yield properties are controlling criteria, the designer can interchange rolled, forged, welded, and cast steel.

Ductility. The ductility of cast steels is nearly the same as that of forged, rolled, or welded steels of the same hardness. The longitudinal properties of rolled or forged steel are somewhat higher than the properties of cast steel or weld metal. However, the transverse properties are lower by an amount that depends on the amount of working. When service conditions involve multidirectional loading, the nondirectional characteristic of cast steels may be advantageous.

Toughness. The notched-bar impact test is often used as a measure of the toughness of materials and is particularly useful in determining the transition temperature from ductile to brittle fracture. Nil ductility transition temperature (NDTT) as determined as per method ASTM E 208, lateral expansion values, and the energy absorbed values at specific temperatures are some of the different criteria for evaluating impact properties. The impact properties of wrought steels are usually listed for the longitudinal direction; the values shown are higher than those for cast steels of equivalent composition and thermal treatment. The transverse impact properties of wrought steels are usually 50 to 70% of those in the longitudinal direction above the transition temperature and, in some conditions of composition and degree of working, even lower. Because cast steels are nondirectional, their impact properties usually fall somewhere between the longitudinal and transverse properties of wrought steel of similar composition.

Impact properties are controlled by microstructure and, in general, are not significantly affected by microshrinkage or hydrogen. The effect of microstructure, as controlled by chemical composition and heat treatment, is discussed in the article "Service Characteristics of Carbon and Alloy Steels" in this Section (see the sub-section on "Notch Toughness of Steels"). Curves of impact energy versus temperature for casting steels designed specifically for pressure-containing parts for low-temperature service are presented in Fig. 4. These curves illustrate the significant changes in impact properties that can be effected by changes in steel grade and/or heat treatment.

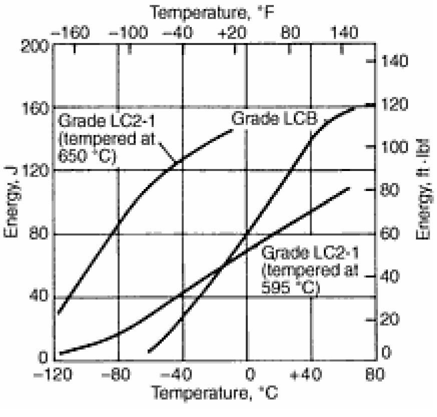


Fig. 4 Effect of temperature on Charpy V-notch impact energy of cast steels for low-temperature service. Steel grades conformed to ASTM A 352. Heat treatments were as follows: grade LCB (0.30% C max, 1.00% Mn max steel), water quenched from 890 °C (1650 °F), tempered at 650 °C (1200 °F) and water quenched, aged 40 h at 425 °C (800 °F), and stress relieved 40 h at 595 °C (1100 °F); grade LC2-1 (Ni-Cr-Mo steel), normalized at 955 °C (1750 °F) and air cooled, reheated to 890 °C (1650 °F) and water quenched, either tempered at 595 °C (1100 °F) and aged 40 h at 425 °C (800 °F) or tempered at 650 °C (1200 °F) and aged 64 h at 425 °C (800 °F). All specimens were taken at locations greater than one-fourth the thickness in from the surface of test blocks 51 by 210 by 229 mm (2 by $8\frac{1}{4}$ by 9 in.) having an ASTM grain size of 6 to 8. The curves represent average values for several tests at each test temperature.

Section size also affects the impact properties that are obtained. Figure 5 illustrates this effect for one of the grades of steel castings described in Fig. 4 (grade LCB). When the section size is increased from 25 to 127 mm (1 to 5 in.), the temperature at which the impact energy is reduced to an average of 18 J (13 ft · lbf) is increased by 28 °C (50 °F).

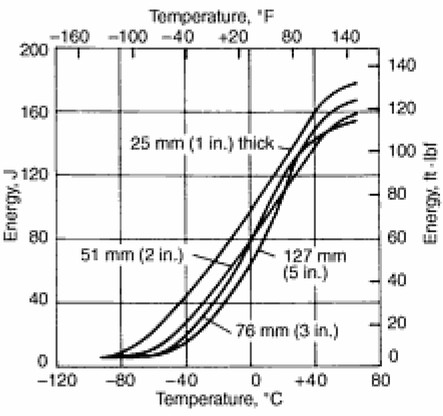


Fig. 5 Effect of section thickness on Charpy V-notch impact curves of grade LCB steel castings. Steel grade conformed to ASTM A 352. Heat treatment was the same as for Fig. 4. All specimens were taken at locations greater than one-fourth the thickness in from the surface of test blocks of four sizes: 25 by 25 by 279 mm (1 by 1 by 11 in.), 51 by 210 by 229 mm (2 by $8\frac{1}{4}$ by 9 in.), 76 by 229 by 283 mm (3 by 9 by $11\frac{1}{8}$ in.), and 127 by 381 by 381 mm (5 by 15 by 15 in.). The ASTM grain size of the blocks was 6 to 8. The curves represent average values for several tests at each test temperature.

Fatigue Strength. For cast steels, the fatigue strength, or endurance limits, as determined by tests on smooth bars is generally in the range of 40 to 50% of the tensile strength. Figure 6 compares the fatigue endurance limits of both wrought and cast steels. Although the unnotched fatigue endurance limit or wrought steels is higher, they are much more notch sensitive than are cast steels.

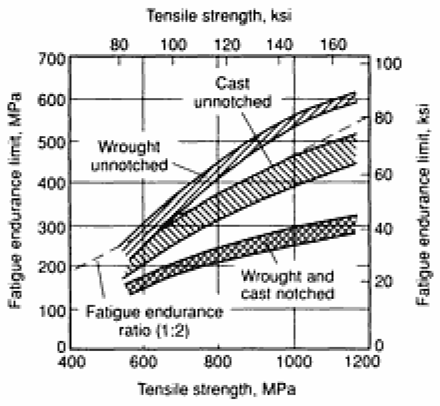


Fig. 6 Fatigue endurance limit versus tensile strength for notched and unnotched cast and wrought steels with various heat treatments. Data obtained in R.R. Moore rotating-beam fatigue tests; theoretical stress concentration factor = 2.2

Section Size and Mass Effects. The size of a cast coupon or casting can have a marked effect on its mechanical properties. This effect reflects the influence of section size on the cooling rates achieved during heat treatment; a larger section has more mass, which slows the cooling rates within the section and thus affects the microstructure and mechanical properties achieved during cooling. The effect of increasing section size on the mechanical properties of a medium-carbon cast steel in the annealed and as-cast condition is shown in Fig. 7. Because of section size effects, the results of tests on specimens taken from very heavy sections and from large castings are helpful in predicting minimum properties in cast steel parts.

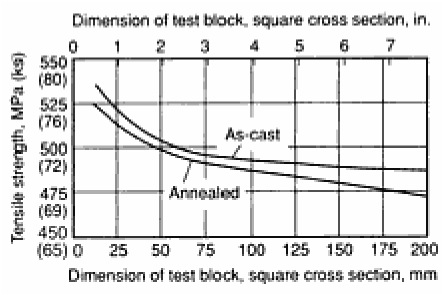


Fig. 7 Effect of section size on tensile strength of medium-carbon steel castings

Low-Carbon Cast Steels

Low-carbon cast steels are those with a carbon content of less than 0.20%. Most of the tonnage produced in the low-carbon classification contains between 0.16 and 0.19% C, with 0.50 to 0.80% Mn, 0.05% P (max), 0.06% S (max), and 0.35% to 0.70% Si. In order to obtain high magnetic properties in electrical equipment, the manganese content is usually held between 0.10 and 0.20%.

Low-carbon steel castings are made in two important classes. One may be termed railroad castings, and the other miscellaneous jobbing castings. The railroad castings consist mainly of comparatively symmetrical and well-designed castings for which adverse stress conditions have been carefully studied and avoided. Miscellaneous jobbing castings present a wide variation in design and frequently involve the joining of light and heavy sections. Varying sections make it more difficult to avoid high residual stress in the as-cast shape. Because residual stresses of large magnitude cannot be tolerated in many service applications, stress relieving becomes necessary. Therefore, the annealing of those castings is decidedly beneficial even though it may cause little improvement of mechanical properties.

Figure 2 includes the mechanical properties of carbon cast steels with low-carbon contents within the range of about 0.10 to 0.20%. There is very little difference between the properties of the low-carbon

Medium-Carbon Cast Steels

The medium-carbon grades of cast steel contain 0.20 to 0.50% C and represent the bulk of steel casting production. In addition to carbon, they contain 0.50 to 1.50% Mn, 0.05% P (max), 0.06% S (max), and 0.35 to 0.80% Si. The mechanical properties at room temperature of cast steels containing from 0.20 to 0.50% C are included in Fig. 2. Steels in this carbon range are always heat treated, which relieves casting strains, refines the as-cast structure, and improves the ductility of the steel. A very large proportion of steel castings of this grade are given a normalizing treatment, followed by a tempering treatment.

High-Carbon Cast Steels

Cast steels containing more than 0.50% C are classified as high-carbon steels. This grade also contains 0.50 to 1.50% Mn, 0.05% P (max), 0.05% S (max), and 0.35 to 0.70% Si. The mechanical properties of high-carbon steels at room temperature are shown in Fig. 2. High-carbon cast steels are often fully annealed. Occasionally, a normalizing and tempering treatment is given, and for certain applications an oil quenching and tempering treatment may be used.

The microstructure of high-carbon steel is controlled by the heat treatment. Carbon also has a marked influence, for example, giving 100% pearlitic structure at eutectoid composition ($\sim$0.83% carbon). Higher proportions of carbon than eutectoid composition will increase the proeutectoid cementite, which is detrimental to the casting if it forms a network at the grain boundaries because of improper heat treatment (for example, slow cooling from above the A_{cm} temperature). Faster cooling will prevent the formation of this network and, hence, improve the properties.

Low-Alloy Cast Steels

Low-alloy cast steels contain a total alloy content of less than 8%. These steels have been developed and used extensively for meeting special requirements that cannot be met by ordinary plain carbon steels with low hardenability. The addition of alloys to plain carbon steel castings may be made for any of several reasons, such as to provide higher hardenability, increased wear resistance, higher impact resistance at increased strength, good machinability even at higher hardness, higher strength at elevated and low temperatures, and better resistance to corrosion and oxidation than the plain carbon steel castings. These materials are produced to meet tensile strength requirements of 485 to 1380 MPa (70 to 200 ksi), together with some of the above special requirements. Figure 3 shows typical room-temperature mechanical properties of low-alloy steels plotted against yield strength. These properties are, of course, a function of alloy content, heat treatment, and section size.

Bearing Steels

Introduction

ROLLING-ELEMENT BEARINGS, whether ball bearings or roller bearings with spherical, straight, or tapered rollers, are fabricated from a wide variety of steels. In a broad sense, bearing steels can be divided into two classes: standard bearing steels are intended for normal service conditions (see the discussion which follows); whereas special-purpose bearing steels are used for either extended fatigue life or excessive operating conditions of temperature and corrosion.

Bearings for normal service conditions, a category that includes more than 95% of all rolling-element bearings, are applicable when:

- Maximum temperatures are of the order of 120 to 150 °C (250 to 300 °F), although brief excursions to 175 °C (350 °F) may be tolerated.
- Minimum ambient temperatures are about -50 °C (-60 °F).
- The contact surfaces are lubricated with such materials as oil, grease, or mist.
- The maximum Hertzian contact stresses are of the order of 2.1 to 3.1 GPa (300 to 450 ksi).

Bearings used under normal service conditions also experience the effects of vibration, shock, misalignment, debris, and handling. Therefore, the fabrication material must provide toughness, a degree of temper resistance, and microstructural stability under temperature extremes. The material must also exhibit the obvious requirement of surface hardness for wear and fatigue resistance, particularly rolling-contact fatigue resistance.

Bearing Steel Production and Quality

Apart from a satisfactory microstructure, which is obtained through the proper combination of steel grade and heat treatment, the single most important factor in achieving levels of rolling-contact fatigue life in bearings is the cleanliness, or freedom from harmful nonmetallic inclusions, of the steel. Bearing steels can be produced by one of these techniques:

- Clean-steel air-melt practices
- Electroslag remelting
- Air melting followed by vacuum arc remelting
- Vacuum induction melting followed by vacuum arc remelting (VIM/VAR)

Cleanliness, cost, and reliability can increase depending on which practice is chosen.

Bearing steel cleanliness is most commonly rated by using microscopic techniques, such as those defined in ASTM A 295 for high-carbon steels and A 534 for carburizing steels. The worst fields found in metallographically prepared sections of the steel can be compared with rating charts (J-K charts) according to the type of inclusion: sulfides, stringer-type oxides, silicates, and globular-type oxides.

Bearing steel cleanliness can also be rated by oxygen analysis, the magnetic particle method (AMS 2301, AMS 2300), and ultrasonic methods. Quantified ultrasonic results are supplemented with inclusion imaging and length verification using acoustic microscopy. These tools, along with energy-dispersive or wavelength-dispersive chemical analyses using scanning electron microscopy, have confirmed the aluminum oxide stringers relate directly with bearing fatigue life under operating conditions that promote material fatigue. The size distribution and the total quantity of inclusion stringers in a given group of bearings has been shown to relate to performance (fatigue life) through a summation of the inclusion stringer lengths per unit volume of steel.

The total length of inclusion stringers per unit volume is the abscissa on Fig. 1. The steel cleanness range starts with an earlier vacuum carbon deoxidation steel process method to the precipitation-shrouded version of today's air-melt steels and to today's vacuum-arc remelted steel. As shown in Fig. 1, the over-all fatigue life range is more than an order of magnitude. VIM/VAR steel lives exceed even the VAR steel lives so that even though the present-day air-melt steels do give better lives, the vacuum-processed steels are meeting the fatigue life requirements for the extended-life applications.

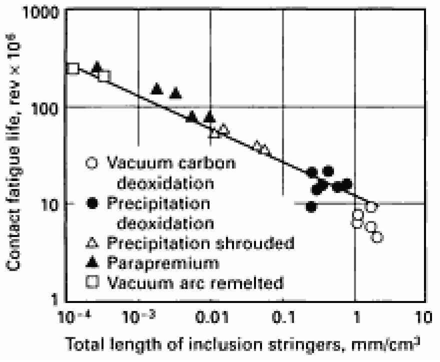


Fig. 1 Effect of total length of inclusion stringers on the rolling contact fatigue life of a 220 mm (8.7 in.) bore tapered roller bearing inner race as a function of steel cleanness

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Standard Bearing Steels

The steel used in rolling bearings for normal requirements such as industrial or automotive applications is an alloy steel with alloy content, in addition to carbon, that runs from ∼1.5 to 6%, depending on the bearing ring cross section and hardenability requirements. Typical standard bearing steel compositions for high-carbon or through-hardened steels are given in Table 1, and standard bearing steel compositions for low-carbon or carburizing bearing steels are given in Table 2. Both steels are used depending on specific service condition needs. High-carbon steels provide the following advantages:

- Ability to carry somewhat higher contact stresses, such as those encountered in point contact loading in ball bearings
- A simpler quench and temper heat treatment when compared to carburizing
- Potentially greater dimensional stability under temperature extremes because of their characteristically lower content of retained austenite

Table 1 Nominal compositions of high-carbon bearing steels

Grade	Composition, %					
	C	**Mn**	**Si**	**Cr**	**Ni**	Mo
AISI 52100	1.04	0.35	0.25	1.45	. . .	**. . .**
ASTM A 485-1	0.97	1.10	0.60	1.05	. . .	**. . .**
ASTM A 485-3	1.02	0.78	0.22	1.30	. . .	**0.25**
TBS-9	0.95	0.65	0.22	0.50	0.25 max	**0.12**
SUJ 1(a)	1.02	<0.50	0.25	1.05	<0.25	**<0.08**
105Cr6(b)	0.97	0.32	0.25	1.52	. . .	**. . .**

(a) Japanese grade.

(b) German grade.

(c) Russian grade

Table 2 Nominal compositions of carburizing bearing steels

Grade	Composition, %					
	C	**Mn**	**Si**	**Cr**	**Ni**	Mo
4118	0.20	0.80	0.22	0.50	. . .	**0.11**
5120	0.20	0.80	0.22	0.80	. . .	**. . .**
8620	0.20	0.80	0.22	0.50	0.55	**0.20**
4620	0.20	0.55	0.22	. . .	1.82	**0.25**

4320	0.20	0.55	0.22	0.50	1.82	**0.25**
3310	0.10	0.52	0.22	1.57	3.50	**. . .**
SCM420	0.20	0.72	0.25	1.05	. . .	**0.22**
20MnCr5	**0.20**	**1.25**	**0.27**	**1.15**	**. . .**	**. . .**

Carburizing steels, on the other hand, offer the following advantages:

- Greater surface ductility (due to their retained austenite content) to better resist the stress-raising effects of asperities, misalignment, and debris particles
- A higher level of core toughness to resist through-section fracture under severe service conditions
- A compressive residual surface stress condition to resist bending loads imposed on the ribs of roller bearings, and to reduce the rate of fatigue crack propagation through the cross section.
- Easier machining of the base material in manufacturing

Surface hardness on the order of 58 to 64 HRC is present for either high-carbon or carburizing bearing steels: however, there are some differences in the core hardnesses of these two types of materials. The data in Table 3 show that the strength and toughness of the core are greater in the quenched and tempered low-carbon steels than in the unhardened portion of an induction-hardened high-carbon steel bearing part.

Table 3 Core properties of carburized versus induction-hardened components

Material	**Hardness, HB**	**Yield strength**		**Ultimate tensile strength**		**Impact energy**		Machining[a], %
		MPa	**ksi**	**MPa**	**ksi**	**J**	**ft · lbf**	
8620[b]	30-45 HRC	825-965	120-140	1105-1240	160-180	55-110	40-80	**65**
5160[c]	197	275	40	725	105	10	7	**55**
1095[c]	192	380	55	655	95	3	2	**45**

(a) Where 1212 carbon steel represents 100%.

(b) Quenched and tempered.

(c) Annealed

From a surface fatigue standpoint, it is necessary to maintain sufficient hardness on and below the surface to resist abrasive/adhesive wear and to minimize contact fatigue in the whole region of the surface and below so that the material strength at each point is higher than the surface or subsurface shear stresses that occur from a loaded Hertzian surface stress. Figure 2 shows an estimated relationship between the hardness and shear yield strength that is applicable to either steel type. The success of a given steel in a bearing application is not as much a function of the steel type as how it is treated. Fatigue resistance generally increases with hardness; the maximum depends on the steel type. Figure 3 compares the bending fatigue lives of through-carbon and carburized steels as a function of surface hardness. In bending fatigue, the combination of compressive residual surface stresses with a higher composite section toughness gives the advantage to the carburized steel.

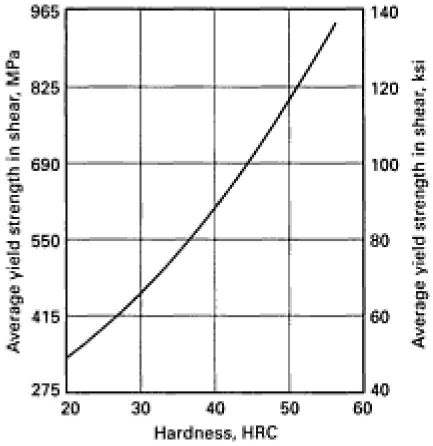


Fig. 2 Plot of shear yield strength versus hardness for typical bearing steel

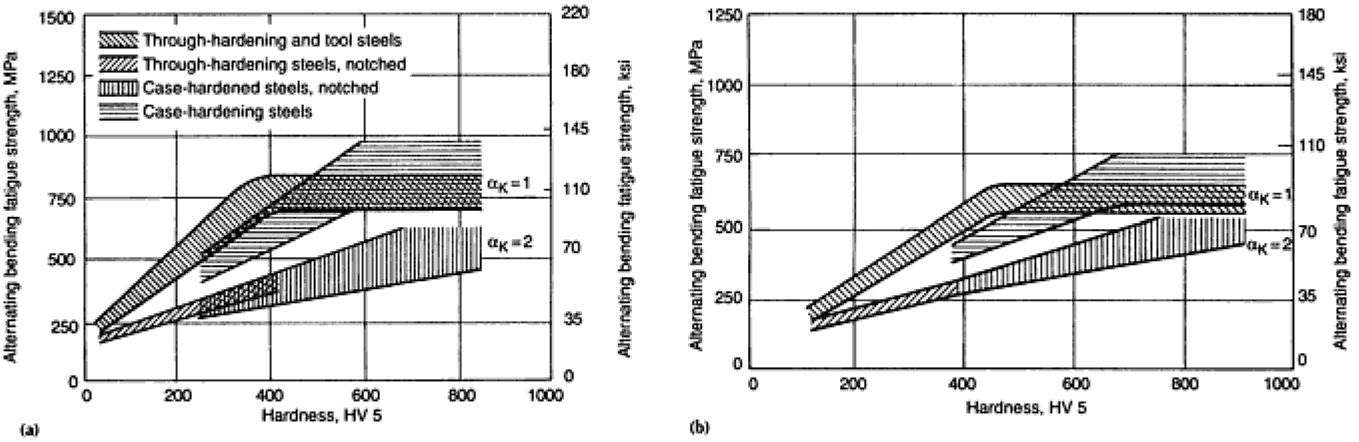


Fig. 3 Rotating-beam fatigue strength of cast-hardening and through-hardening steels as a function of surface hardness. (a) Testpiece diameter of 6mm (0.25 in.), and triangular torque. (b) Testpiece diameter of 12 mm (0.5 in.), constant torque. α_K is the stress-concentration factor.

Characteristics of High-Carbon Bearing Steels. The matrix of hardened-and-tempered bearing steels is high-carbon martensite, containing primary carbides and 5 to 10% retained austenite. The hardness throughout the section is typically 60 to 64 HRC. Table 1 lists the compositions of selected high-carbon bearing steels currently in use. The first grades are listed in order of increasing hardenability; they are applied to bearing sections of increasing thickness to ensure freedom from nonmartensitic transformations in hardening. Grade TBS-9 is a lower-chromium bearing steel, which, because of its residual alloy content, has a hardenability similar to that of SAE-AISI 52100. The remaining steels are representative of overseas steels applied to bearing components.

Characteristics of Carburizing Bearing Steels. The case microstructure of carburized bearing steels consists of high-carbon martensite with retained austenite in the range of 15 to 40% (higher amounts of retained austenite increase rolling-contact fatigue life). Case hardness is typically 58 to 64 HRC. In the core of carburized bearings, the microstructure consists of low-carbon martensite; it also often contains variable amounts of bainite and ferrite. The core hardness may vary from 25 to 48 HRC.

Table 2 lists compositions of typical carburizing bearing steels. The SAE-AISI grades are listed in approximate order of increasing hardenability or section size applicability. SCM420 and 20MnCr5 are Japanese and German grades, respectively, found in carburized bearing components. In addition to standard SAE-AISI grades, bearing steels can also be designed so that their hardenability matches the requirements of specific section thicknesses. Alloy conservation and a more consistent heat-treating response are benefits of using specially designed bearing steels.

The selection of a carburizing steel for a specific bearing section is based on the heat-treating practice of the producer, either direct quenching from carburizing or reheating for quenching, and on the characteristics of the quenching equipment. The importance of a proper case microstructure to the ability of a bearing to resist pitting fatigue is illustrated in Fig. 4. In particular, the presence of pearlite, resulting from a mismatch of quenching conditions and case hardenability, is shown to have a detrimental effect.

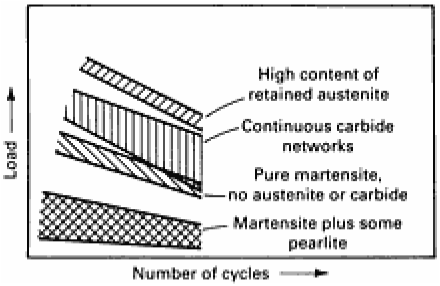


Fig. 4 Effect of surface microstructure on the shape of *S*-*N* curve for surface fatigue (pitting)

Special-Purpose Bearing Steels

When bearing service temperatures exceed about 150 °C (300 °F), common low-alloy steels cannot maintain the necessary surface hardness to provide satisfactory fatigue life. The low corrosion resistance of these steels makes them susceptible to attack by environmental moisture, as well as aggressive gaseous or liquid contaminants. Therefore, specialized steels are often applied when these service conditions exist.

High-Temperature Service Bearing Steels. Table 4 lists the compositions of certain bearing steels suited for high-temperature service. These steels are typically alloyed with carbide-stabilizing elements such as chromium, molybdenum, vanadium, and silicon to improve their hot hardness and temper resistance. The listed maximum operating temperatures are those at which the hardness at temperature falls below a minimum of 58 HRC. Figure 5 compares the hot hardness behavior of various tool and bearing steels.

Table 4 Nominal compositions of high-temperature bearing steels

Steel	**Composition, %**								Maximum operating temperature[a]	
	C	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**V**	**Other**	**°C**	°F
M50	0.85	. . .	. . .	4.10	. . .	4.25	1.00	. . .	315	**600**
M50-NiL	0.13	0.25	0.20	4.20	3.40	4.25	1.20	. . .	315	**600**
Pyrowear 53	0.10	0.35	1.00	1.00	2.00	3.25	0.10	2.00 Cu	205	**400**
CBS-600	0.19	0.60	1.10	1.45	. . .	1.00	. . .	0.06 Al	230	**450**
Vasco X2-M	0.15	0.29	0.88	5.00	. . .	1.50	0.5	1.50 W	230	**450**
CBS-1000M	0.13	0.55	0.50	1.05	3.00	4.50	0.40	0.06 Al	315	**600**

(a) Maximum service temperature, based on a minimum hot hardness of 58 HRC

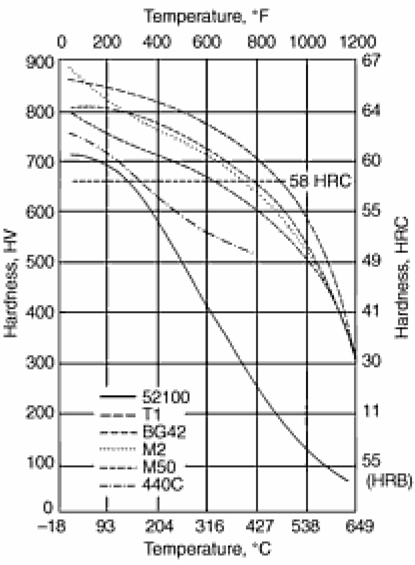


Fig. 5 Hot hardness of homogeneous high-carbon steels for service above 150 °C (300 °F). The dashed line at 58 HRC indicates the maximum service temperature at which a basic dynamic load capacity of about 2100 MPa (300 ksi) can be supported in bearings and gears

An important application of the high-temperature bearing steels is aircraft and stationary turbine engines. Bearings made from M50 steel have been used in engine applications for many years. Jet engine speeds are being continually increased in order to improve performance and efficiency; therefore, the bearing materials used in these engines must have increased section toughness to withstand the stresses that result from higher centrifugal forces. For this reason, the carburizing high-temperature bearing steels, such as M50-NiL and CBS-1000M, are receiving much attention. The core toughness of these steels is more than twice that of the through-hardening steels.

In general, high-temperature bearing steels require more care in the carburizing process than conventional low-alloy carburizing steels. Because of the high content of chromium and silicon in the high-temperature steels, some precarburizing treatment, such as preoxidation, is always necessary to promote satisfactory carburizing.

Corrosion-Resistant Bearing Steels. Bearings that require the highest corrosion resistance necessitate the use of stainless grades with greater than 12% Cr. At this time, no satisfactory carburizing technique has been developed for these grades. Thus, all corrosion-resistant bearing steels are of the through-hardening type (Table 5). Steels such as the 440C modification, CRB-7, and BG42 also offer good high-temperature hardness.

Table 5 Nominal compositions of corrosion-resistant bearing steels

Grade	Composition, %							
	C	**Mn**	**Si**	**Cr**	**Mo**	**W**	**V**	Nb
BG42	1.15	0.50	0.30	14.50	4.00	. . .	1.2	. . .
440C	1.00	0.40	0.30	17.00	0.50	. . .	. . .	. . .
440C modified	1.05	0.40	0.30	14.00	4.00	. . .	. . .	. . .

High-Strength Structural and High-Strength Low-Alloy Steels

Introduction

THE STEELS discussed in this article are characterized by higher yield strengths than those of plain carbon structural steels. There are three categories: (a) carbon steel grades having minimum yield strengths of 275 to 550 MPa (40 to 80 ksi); (b) microalloyed high-strength low-alloy (HSLA) steels, with improved properties that result from a combination of alloy additions and controlled hot rolling (mechanical properties of HSLA steels are intermediate between those of plain carbon structural steels and heat-treated high-strength carbon and low-alloy constructional steels); and (c) quenched-and-tempered low-alloy steel grades having minimum yield strengths of 550 to 1030 MPa (80 to 150 ksi) that meet the requirements of specifications such as ASTM A 514. Steels with even higher yield strength levels (greater than 1380 MPa, or 200 ksi) are described in the article "Ultrahigh-Strength Steels" which immediately follows in this Section.

High-strength and HSLA grades are generally available in all standard wrought forms: sheet, strip, plate, structural shapes, bars, bar-size shapes, and special sections. These steels are also furnished as cold rolled sheet or strip in gages up to about 1.6 mm ($\frac{1}{16}$ in.) for greater control of thickness in structures such as trailer bodies or for improved surface finish in instances where parts are to be plated.

The heat treated grades are available as plate, bar and, occasionally, sheet and structural shapes. When intended for applications involving hot forming, they are generally purchased in the non-heat-treated condition. Also, semifinished mill products are available for forging. After forming or forging, such products may be heat treated to develop high strength.

High-strength steels are produced to specified mechanical properties, which may differ slightly for different thickness ranges. Maximum limits of chemical composition are generally published because the carbon and alloy contents are varied as necessary to maintain mechanical properties in products of various thicknesses.

High-Strength Structural Carbon Steels

High-strength structural carbon steels are basically carbon-manganese or carbon-manganese-silicon steels, with some grades containing small alloying additions of other elements. Such steels are used in either the as-hot-rolled or heat-treated (normalized or quenched and tempered) condition. As listed in Table 1, the yield strength of quenched and tempered carbon-manganese steel plate varies from 315 to 550 MPa (46 to 80 ksi), depending on section thickness. Minimum Charpy V-notch impact toughness may be as high as 27 to 34 J (20 to 25 ft · lbf) at temperatures as low as -68 °C (-90 °F) for quenched and tempered carbon steel having yield strengths of 345 MPa (50 ksi). However, for quenched and tempered carbon steel with 690 MPa (100 ksi) yield strengths (Table 1), the impact values are lower, normally about 20 J (15 ft · lbf) at -60 °C (-75 °F). All grades can be grain refined with aluminum to improve toughness.

Table 1 Typical compositions, tensile properties, and product sizes of high-strength structural carbon steels

Specification and grade or class	**Product form**	**Product thickness(a)**		**Heat analysis composition(b), %**				**Yield strength**		**Tensile strength**		Elongation in 200 mm (8 in.), %
		mm	**in.**	**Carbon**	**Manganese**	**Silicon**	**Copper**	**MPa**	**ksi**	**MPa**	**ksi**	
As-hot-rolled carbon-manganese steels												
ASTM A 529	Bar, plate, and shapes	13	$\frac{1}{2}$	0.27	1.20	. . .	0.20(c)	290	42	415-585	60-85	**19**
ASTM A 612	Plate	13	$\frac{1}{2}$	0.25	1.00-1.35	0.15-0.40	0.35	345	50	570-725	83-165	**16**
		20	$\frac{3}{4}$	0.25	1.00-1.35	0.15-0.40	0.35	345	50	560-695	81-101	**16**
		20-25	$\frac{3}{4}$-1	0.25	1.00-1.50	0.15-0.50	0.35	345	50	560-695	81-101	**16**
ASTM A 570, grades 45, 50, 55	Sheet	6	0.230	0.25	1.35	. . .	0.20(c)	310-380	45-55	415-480	60-70	**14-10**
ASTM A 662, grade B	Plate	40	$1\frac{1}{2}$	0.19	0.85-1.50	0.15-0.40	. . .	275	40	450-585	65-85	**20**

ASTM A 662, grade C	Plate	40	$1\frac{1}{2}$	0.20	1.00-1.60	0.15-0.50	. . .	295	43	485-620	70-90	**18**
Normalized structural carbon-manganese steels												
ASTM A 537, class 1	Plate	40	$1\frac{1}{2}$	0.24	0.70-1.35	0.15-0.50	0.35	345	50	485-620	70-90	**18**
	Plate	40-65	$1\frac{1}{2}$ - $2\frac{1}{2}$	0.24	1.00-1.60	0.15-0.50	0.35	345	50	485-620	70-90	**18**
	Plate	65-100	$2\frac{1}{2}$ -4	0.24	1.00-1.60	0.15-0.50	0.35	310	45	450-585	65-85	**18**
ASTM A 612	Plate	**Same as ASTM A 612 in the as-rolled condition, but can be normalized for improved impact toughness**										
ASTM A 633, grade A	Plate	100	4	0.18	1.00-1.35	0.15-0.50	. . .	290	42	430-570	63-83	**18**
ASTM A 662, grade A	Plate	40-50	$1\frac{1}{2}$ -2	0.14	0.90-1.35	0.15-0.40	. . .	275	40	400-540	58-78	**20**
ASTM A 662, grade B	Plate	40-50	$1\frac{1}{2}$ -2	0.19	0.85-1.50	0.15-0.40	. . .	275	40	450-585	65-85	**20**
ASTM A 662, grade C	Plate	40-50	$1\frac{1}{2}$ -2	0.20	1.00-1.60	0.15-0.50	. . .	295	43	485-620	70-90	**18**
ASTM A 738, grade A	Plate	65(d)	$2\frac{1}{2}$ (d)	0.24	1.50(d)	0.15-0.50	0.35	310	45	515-655	75-95	**20(e)**
ASTM A 737, grade B	Plate	100	4	0.20	1.15-1.50	0.15-0.50	. . .	345	50	485-620	70-90	**18**
Quenched and tempered structural carbon-manganese steels												
SAE J 368a, grade Q550	Plate	20	$\frac{3}{4}$	0.20	1.35	. . .	. . .	550	80	655-795	95-115	**18(e)**
ASTM A 537, class 2	Plate	40	$1\frac{1}{2}$	0.24	0.70-1.35	0.15-0.50	0.35	415	60	550-690	80-100	**22(e)**
		40-65	$1\frac{1}{2}$ -	0.24	1.00-1.60	0.15-0.50	0.35	415	60	550-690	80-100	**22(e)**

			$2\frac{1}{2}$								
		65-100	$2\frac{1}{2}$-4	0.24	1.00-1.60	0.15-0.50	0.35	380	55	515-655	75-95	**22(e)**
		100-150	4-6	0.24	1.00-1.60	0.15-0.50	0.35	315	46	485-620	70-90	**22(e)**
ASTM A 678, grade A	Plate	40	$1\frac{1}{2}$	0.16	0.90-1.50	0.15-0.50	0.20(c)	345	50	485-620	70-90	**22(e)**
ASTM A 678, grade B	Plate	40	$1\frac{1}{2}$	0.20	0.70-1.35	0.15-0.50	0.20(c)	415	60	550-690	80-100	**22(e)**
		40-65	$1\frac{1}{2}$-$2\frac{1}{2}$	0.20	1.00-1.60	0.15-0.50	0.20(c)	415	60	550-690	80-100	**22(e)**
ASTM A 678, grade C	Plate	20	$\frac{3}{4}$	0.22	1.00-1.60	0.20-0.50	0.20(c)	515	75	655-790	95-115	**19(e)**
		20-40	$\frac{3}{4}$-$1\frac{1}{2}$	0.22	1.00-1.60	0.20-0.50	0.20(c)	485	70	620-760	90-100	**19(e)**
		40-50	$1\frac{1}{2}$-2	0.22	1.00-1.60	0.20-0.50	0.20(c)	450	65	585-720	85-105	**19(e)**
ASTM A 738, grade B	Plate	65	$2\frac{1}{2}$	0.20	0.90-1.50	0.15-0.55	0.35	415	60	585-705	85-102	**20(e)**
ASTM A 738, grade C	Plate	65	$2\frac{1}{2}$	0.20	1.50	0.15-0.50	0.35	415	60	550-690	80-100	**22(e)**
		65-100	$2\frac{1}{2}$-4	0.20	1.62	0.15-0.50	0.35	380	55	515-655	75-95	**22(e)**
		100-150	**4-6**	**0.20**	**1.62**	**0.15-0.50**	**0.35**	**315**	**46**	**485-620**	**70-90**	**20(e)**

(a) Product thicknesses are a maximum unless a range is given.

(b) Compositions are a maximum unless a range is given or if otherwise specified in footnotes. Residual amounts of sulfur and phosphorus are limited in all grades and have specified maximums of 0.035 to 0.04% P (max) and 0.04 to 0.05% S (max), depending on the specification.

(c) Minimum amount of copper if specified.

(d) Over 65 mm (2.5 in.), ASTM A 738 grade A requires quenching and tempering and 1.62% Mn (max) to achieve the specified strength levels.

(e) Elongation in 50 mm (2 in.)

In addition to high-strength plate applications, quenched and tempered carbon-manganese steels are used for shafts and couplings. Steels with 0.40 to 0.60% C are used for railway wheels, tires, and axles, while those with higher carbon contents can be used as high-strength wire laminated spring materials, often with silicon-manganese or chromium-vanadium additions. The higher-carbon steels are also used for rails (0.7% C) and, over a range of carbon contents (typically, 0.20-0.50% C, for reinforcing bar.

High-Strength Low-Alloy Steels

HSLA steels, or microalloyed steels, are designed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional carbon steels. They are not considered to be alloy steels in the normal sense because they are designed to meet specific mechanical properties rather than a chemical composition. (HSLA steels have yield strengths greater than 275 MPa, or 40 ksi.) The chemical composition of a specific HSLA steel may vary for different product thicknesses to meet mechanical property requirements. The HSLA steels have low carbon content (0.05 to ~0.25% C) in order to produce adequate formability and weldability, and they have manganese content up to 2.0%. Small quantities of chromium, nickel, molybdenum, copper, nitrogen, vanadium, niobium, titanium, and zirconium are used in various combinations.

High-strength low-alloy steels are primarily hot-rolled into the usual wrought product forms (sheet, strip, bar, plate, and structural sections) and are commonly furnished in the as-rolled condition. However, the production of hot-rolled HSLA products may also involve special hot-mill processing that further improves the mechanical properties of some HSLA steels and product forms. These processing methods include:

- *The controlled rolling* of precipitation-strengthened HSLA steels to obtain fine austenite grains and/or highly deformed (pancaked) austenite grains. During cooling, these austenite grains transform into fine ferrite grains that greatly enhance toughness while improving yield strength.
- *The accelerated cooling* of, preferably, controlled-rolled HSLA steels to produce fine ferrite grains during the transformation of austenite. These cooling rates cannot be rapid enough to form acicular ferrite, nor can they be slow enough that high coiling temperatures result thereby causing the overaging of precipitates.
- *The quenching or accelerated air or water cooling* of low-carbon steels ($\leq$0.08% C) that possess adequate hardenability to transform into low-carbon bainite (acicular ferrite). This microstructure offers an excellent combination of high yield strengths (275 to 690 MPa, or 60 to 100 ksi), excellent weldability and formability, and high toughness. (Controlled rolling is necessary for low ductile-brittle transition temperatures.)
- *The normalizing* of vanadium-containing HSLA steels. This process refines grain size, thereby improving toughness and yield strength.
- *The intercritical annealing* of HSLA steels to obtain a dual-phase microstructure (martensite islands dispersed in a ferrite matrix). This microstructure exhibits a lower yield strength but, because of rapid work-hardening capability, provides a better combination of ductility and tensile strength than conventional HSLA steels and also improved formability.

The use of these processing methods for controlling/enhancing the properties of HSLA steels is described in the article "Steelmaking Practices and Their Influence on Properties" in this Handbook.

Table 2 Summary of characteristics and intended uses of HSLA steels described in ASTM specifications

ASTM specification[(a)]	**Title**	**Alloying elements**[(b)]	**Available mill forms**	**Special characteristics**	Intended uses
A 242	High-strength low-alloy structural steel	Cr, Cu, N, Ni, Si, Ti, V, Zr	Plate, bar, and shapes ≤100 mm (4 in.) in thickness	Atmospheric-corrosion resistance four times that of carbon steel	**Structural members in welded, bolted, or riveted construction**
A 572	High-strength low-alloy niobium-vanadium steels of structural quality	Nb, V, N	Plate, bar, shapes, and sheet piling ≤150 mm (6 in.) in thickness	Yield strengths of 290 to 450 MPa (42 to 65 ksi) in six grades	**Welded, bolted, or riveted structures, but mainly bolted or riveted bridges and buildings**
A 588	High-strength low-alloy structural steel with 345 MPa (50 ksi) minimum yield point ≤100 mm (4 in.) in thickness	Nb, V, Cr, Ni, Mo, Cu, Si, Ti, Zr	Plate, bar, and shapes ≤200 mm (8 in.) in thickness	Atmospheric-corrosion resistance four times that of carbon steel; nine grades of similar strength	**Welded, bolted, or riveted structures, but primarily welded bridges and buildings in which weight savings or added durability is important**
A 606	Steel sheet and strip, hot-rolled and cold-rolled, high-strength low-alloy with improved corrosion resistance	Not specified	Hot-rolled and cold-rolled sheet and strip	Atmospheric-corrosion resistance twice that of carbon steel (type 2) or four times that of carbon steel (type 4)	**Structural and miscellaneous purposes for which weight savings or added durability is important**
A 607	Steel sheet and strip, hot-rolled and cold-rolled, high strength low-alloy niobium and/or vanadium	Nb, V, N, Cu	Hot-rolled and cold-rolled sheet and strip	Atmospheric-corrosion resistance twice that of carbon steel, but only when copper content is specified; yield strengths of 310 to 485 MPa (45 to 70 ksi) in six grades	**Structural and miscellaneous purposes for which greater strength or weight savings is important**
A 618	Hot-formed welded and seamless high-strength low-alloy structural tubing	Nb, V, Si, Cu	Square, rectangular, round, and special-shape structural welded or seamless tubing	Three grades of similar yield strength; may be purchased with atmospheric-corrosion resistance twice that of carbon steel	**General structural purposes, included welded, bolted, or riveted bridges and buildings**
A 633	Normalized high-strength low-alloy structural steel	Nb, V, Cr, Ni, Mo, Cu, N, Si	Plate, bar, and shapes ≤150 mm (6 in.) in thickness	Enhanced notch toughness; yield strengths of 290 to 415 MPa (42 to 60 ksi) in five grades	**Welded, bolted, or riveted structures for service at temperatures at or above -45 °C (-50 °F)**
A 656	High-strength, low-alloy, hot-rolled structural vanadium-aluminum-nitrogen and	V, Al, N, Ti, Si	Plate, normally ≤16 mm ($\frac{5}{8}$ in.) in	Yield strength of 552 MPa (80 ksi)	**Truck frames, brackets, crane booms, rail cars, and other applications**

	titanium-aluminum steels		thickness		**for which weight savings is important**
A 690	High-strength low-alloy steel H-piles and sheet piling	Ni, Cu, Si	Structural-quality H-piles and sheet piling	Corrosion resistance two to three times greater than that of carbon steel in the splash zone of marine structures	**Dock walls, sea walls, bulkheads, excavations, and similar structures exposed to seawater**
A 709, grade 50 and 50W	Structural steel	V, Nb, N, Cr, Ni, Mo	All structural-shape groups and plate $\leq$ 100 mm (4 in.) in thickness	Minimum yield strength of 345 MPa (50 ksi). Grade 50W is a weathering steel	**Bridges**
A 714	High-strength low-alloy welded and seamless steel pipe	V, Ni, Cr, Mo, Cu, Nb	Pipe with nominal pipe size diameters of 13 to 660 mm ($\frac{1}{2}$ to 26 in.)	Minimum yield strengths $\leq$345 MPa (50 ksi) and corrosion resistance two to four times that of carbon steel	**Piping**
A 715	Steel sheet and strip, hot-rolled, high-strength low-alloy with improved formability	Nb, V, Cr, Mo, N, Si, Ti, Zr, B	Hot-rolled sheet and strip	Improved formability(c) compared to A 606 and A 607; yield strengths of 345 to 550 MPa (50 to 80 ksi) in four grades	**Structural and miscellaneous applications for which high strength, weight savings, improved formability, and good weldability are important**
A 808	High-strength low-alloy steel with improved notch toughness	V, Nb	Hot-rolled steel plate $\leq$65 mm ($2\frac{1}{2}$ in.) in thickness	Charpy V-notch impact energies of 40 to 60 J (30 to 45 ft · lbf) at -45 °C (-50 °F)	**Railway tank cars**
A 812	High-strength low-alloy steels	V, Nb	Steel sheet in coil form	Yields strengths of 450 to 550 MPa (65 to 85 ksi)	**Welded layered pressure vessels**
A 841	Plate produced by thermomechanical controlled processes	V, Nb, Cr, Mo, Ni	Plates $\leq$100 mm (4 in.) in thickness	Yield strengths of 310 to 345 MPa (45 to 50 ksi)	**Welded pressure vessels**
A 847	Cold-formed welded and seamless high-strength low-alloy structural tubing with improved atmospheric-corrosion resistance	Cu, Cr, Ni, Si, V, Ti, Zr, Nb	Welded tubing with maximum periphery of 1625 mm (64 in.) and wall thickness of 16 mm ($\frac{5}{8}$ in.) or seamless tubing with maximum periphery of 810 mm (32 in.) and wall thickness of 13 mm ($\frac{1}{2}$ in.)	Minimum yield strengths $\leq$345 MPa (50 ksi) with atmospheric-corrosion resistance twice that of carbon	**Round, square, or specially shaped structural tubing for welded, riveted, or bolted construction of bridges and buildings**

A 860	High-strength butt-welding fittings of wrought high-strength low-alloy steel	Cu, Cr, Ni, Mo, V, Nb, Ti	Normalized or quenched-and-tempered wrought fittings	Minimum yield strengths $\leq$485 MPa (70 ksi)	**High-pressure gas and oil transmission lines**
A 871	**High-strength low-alloy steel with atmospheric corrosion resistance**	**V, Nb, Ti, Cu, Mo, Cr**	**As-rolled plate $\leq$35 mm (1$\frac{3}{8}$ in.) in thickness**	**Atmospheric-corrosion resistance four times that of carbon structural steel**	**Tubular structures and poles**

(a) For grades and mechanical properties, see Table 4.

(b) In addition to carbon, manganese, phosphorus, and sulfur. A given grade may contain one or more of the listed elements, but not necessarily all of them; for specified compositional limits, see Table 3.

(c) Obtained by producing killed steel, made to fine grain practice, and with microalloying elements such as niobium, vanadium, titanium, and zirconium in the composition

In addition to hot-rolled products, HSLA steels are also furnished as cold-rolled sheet and forgings. The main advantage of HSLA forgings (as that of as-hot-rolled HSLA products) is that yield strengths in the range of 275 to 485 MPa (40 to 70 ksi) or perhaps higher can be achieved without heat treatment. Base compositions of these microalloyed ferrite-pearlite forgings are typically 0.3 to 0.5% C and 1.4 to 1.6% Mn. Low-carbon bainitic HSLA steel forgings have also been developed.

HSLA Steel Categories. High-strength low-alloy steels include many standard and proprietary grades designed to provide specific desirable combinations of properties such as strength, toughness, formability, weldability, and atmospheric-corrosion resistance. These steels are not considered alloy steels, even though their desired properties are achieved by the use of small alloy additions. Instead, HSLA steels are classified as a separate steel category, which is similar to as-rolled mild-carbon steel with enhanced mechanical properties obtained by the addition of small amounts of alloys and, perhaps, special processing techniques such as controlled rolling. This separate product recognition of HSLA steels is reflected by the fact that HSLA steels are generally priced from the base price for carbon steels, not from the base price for alloy steels. Moreover, HSLA steels are often sold on the basis of minimum mechanical properties, with the specific alloy content left to the discretion of the steel producer.

HSLA steels can be divided into six categories:

- *Weathering steels,* which contain small amounts of alloying elements such as copper and phosphorus for improved atmospheric corrosion resistance and solid-solution strengthening (see the section "Atmospheric Corrosion" in the article "Corrosion Characteristics of Carbon and Alloy Steels" in this Handbook)
- *Microalloyed ferrite-pearlite steels,* which contain very small (generally less than 0.10%) additions of strong carbide or carbonitride-forming elements such as niobium, vanadium, and/or titanium for precipitation strengthening, grain refinement, and possibly transformation temperature control
- *As-rolled pearlitic steels,* which may include carbon-manganese steels but which may also have small additions of other alloying elements to enhance strength, toughness, formability, and weldability
- *Acicular ferrite (low-carbon bainite) steels,* which are low-carbon (less than 0.08% C) steels with an excellent combination of high yield strengths, weldability, formability, and good toughness
- *Dual-phase steels,* which have a microstructure of martensite dispersed in a ferritic matrix and provide a good combination of ductility and high tensile strength
- *Inclusion-shape-controlled steels,* which provide improved ductility and through-thickness toughness by the small additions of calcium, zirconium, or titanium, or perhaps rare earth elements so

that the shape of the sulfide inclusions is changed from elongated stringers to small, dispersed, almost spherical globules

These categories are not necessarily distinct groupings, as an HSLA steel may have characteristics from more than one grouping. For example, all the above types of steels can be inclusion shape controlled. Table 2 describes some typical HSLA steels, their available mill forms, and their intended applications. Tables 3 and 4 list chemical compositions and properties of HSLA steels covered in various ASTM specifications.

Table 3 Compositional limits for HSLA steel grades described in ASTM specifications

ASTM specification[a]	**Type or grade**	**UNS designation**	Heat compositional limits[b], %									
			C	**Mn**	**P**	**S**	**Si**	**Cr**	**Ni**	**Cu**	**V**	Other
A 242	Type 1	K11510	0.15	1.00	0.45	0.05	. . .	. . .	. . .	0.20 min	. . .	**. . .**
A 572	Grade 42	. . .	0.21	1.35[c]	0.04	0.05	0.30[c]	. . .	. . .	0.20 min[d]	. . .	[e]
	Grade 50	. . .	0.23	1.35[c]	0.04	0.05	0.30[c]	. . .	. . .	0.20 min[d]	. . .	[e]
	Grade 60	. . .	0.26	1.35[c]	0.04	0.05	0.30	. . .	. . .	0.20 min[d]	. . .	[e]
	Grade 65	. . .	0.23[c]	1.65[c]	0.04	0.05	0.30	. . .	. . .	0.20 min[d]	. . .	[e]
A 588	Grade A	K11430	0.10-0.19	0.90-1.25	0.04	0.05	0.15-0.30	0.40-0.65	. . .	0.25-0.40	0.02-0.10	**. . .**
	Grade B	K12043	0.20	0.75-1.25	0.04	0.05	0.15-0.30	0.40-0.70	0.25-0.50	0.20-0.40	0.01-0.10	**. . .**
	Grade C	K11538	0.15	0.80-1.35	0.04	0.05	0.15-0.30	0.30-0.50	0.25-0.50	0.20-0.50	0.01-0.10	**. . .**
	Grade D	K11552	0.10-0.20	0.75-1.25	0.04	0.05	0.50-0.90	0.50-0.90	. . .	0.30	. . .	**0.04 Nb, 0.05-0.15 Zr**
	Grade K	. . .	0.17	0.5-1.20	0.04	0.05	0.25-0.50	0.40-0.70	0.40	0.30-0.50	. . .	**0.10 Mo, 0.005-0.05 Nb**
A 606	. . .	. . .	0.22	1.25	. . .	0.05	. . .	. . .	. . .	. . .	. . .	**. . .**

A 607	Grade 45	. . .	0.22	1.35	0.04	0.05	. . .	. . .	. . .	0.20 min(d)	. . .	(e)
	Grade 50	. . .	0.23	1.35	0.04	0.05	. . .	. . .	. . .	0.20 min(d)	. . .	(e)
	Grade 55	. . .	0.25	1.35	0.04	0.05	. . .	. . .	. . .	0.20 min(d)	. . .	(e)
	Grade 60	. . .	0.26	1.50	0.04	0.05	. . .	. . .	. . .	0.20 min(d)	. . .	(e)
	Grade 65	. . .	0.26	1.50	0.04	0.05	. . .	. . .	. . .	0.20 min(d)	. . .	(e)
	Grade 70	. . .	0.26	1.65	0.04	0.05	. . .	. . .	. . .	0.20 min(d)	. . .	(e)
A 618	Grade Ia	. . .	0.15	1.00	0.15	0.05	. . .	. . .	. . .	0.20 min	. . .	**. . .**
	Grade Ib	. . .	0.20	1.35	0.04	0.05	. . .	. . .	. . .	0.20 min(f)	. . .	**. . .**
	Grade II	K12609	0.22	0.85-1.25	0.04	0.05	0.30	. . .	. . .	. . .	0.02 min	**. . .**
	Grade III	K12700	0.23	1.35	0.04	0.05	0.30	. . .	. . .	. . .	0.02 min	**0.005 Nb min(g)**
A 633	Grade A	K01802	0.18	1.00-1.35	0.04	0.05	0.15-0.30	. . .	. . .	. . .	. . .	**0.05 Nb**
	Grade C	K12000	0.20	1.15-1.50	0.04	0.05	0.15-0.50	. . .	. . .	. . .	. . .	**0.01-0.05 Nb**
	Grade D	K02003	0.20	0.70-1.60(c)	0.04	0.05	0.15-0.50	0.25	0.25	0.35	. . .	**0.08 Mo**
	Grade E	K12202	0.22	1.15-1.50	0.04	0.05	0.15-0.50	. . .	. . .	. . .	0.04-0.11	**0.01-0.05 Nb(d), 0.01-0.03 N**
A 656	Type 3	. . .	0.18	1.65	0.025	0.035	0.60	. . .	. . .	. . .	0.08	**0.020 N, 0.005-0.15 Nb**

	Type 7	. . .	0.18	1.65	0.025	0.035	0.60	. . .	. . .	. . .	0.005-0.15	**0.020 N, 0.005-0.10 Nb**
A 690	. . .	K12249	0.22	0.60-0.90	0.08-0.15	0.05	0.10	. . .	0.40-0.75	0.50 min	. . .	**. . .**
A 709	Grade 50, type 1	. . .	0.23	1.35	0.04	0.05	0.40	. . .	. . .	. . .	. . .	**0.005-0.05 Nb**
	Grade 50, type 2	. . .	0.23	1.35	0.04	0.05	0.40	. . .	. . .	. . .	0.01-0.15	**. . .**
	Grade 50, type 3	. . .	0.23	1.35	0.04	0.05	0.40	. . .	. . .	. . .	(h)	**0.05 Nb max**
	Grade 50, type 4	. . .	0.23	1.35	0.04	0.05	0.40	. . .	. . .	. . .	(i)	**0.015 N max**
A 715	. . .	. . .	0.15	1.65	0.025	0.035	. . .	. . .	. . .	. . .	Added as necessary	**Ti, Nb added as necessary**
A 808	. . .	. . .	0.12	1.65	0.04	0.05 max or 0.010 max	0.15-0.50	. . .	. . .	. . .	0.10	**0.02-0.10 Nb, V + Nb = 0.15 max**
A 812	65	. . .	0.23	1.40	0.035	0.04	0.15-0.50(j)	. . .	. . .	. . .	V + Nb = 0.02-0.15	**0.05 Nb max**
	80	. . .	0.23	1.50	0.035	0.04	0.15-0.50	0.35	. . .	. . .	V + Nb = 0.02-0.15	**0.05 Nb max**
A 841	. . .	. . .	0.20	(k)	0.030	0.030	0.15-0.50	0.25	0.25	0.35	0.06	**0.08 Mo, 0.03 Nb, 0.02 Al total**
A 871	**. . .**	**. . .**	**0.20**	**1.50**	**0.04**	**0.05**	**0.90**	**0.90**	**1.25**	**1.00**	**0.10**	**0.25 Mo, 0.15 Zr, 0.05 Nb, 0.05 Ti**

(a) For characteristics and intended uses, see Table 2; for mechanical properties, see Table 4.

(b) If a single value is shown, it is a maximum unless otherwise stated.

(c) Values may vary, or minimum value may exist, depending on product size and mill form.

(d) Optional or when specified.

(e) May be purchased as type 1 (0.005-0.05 Nb), type 2 (0.01-0.15 V), type 3 (0.05 Nb, max, plus 0.02-0.15 V), or type 4 (0.015 N, max, plus V $\geq$4 N).

(f) If chromium and silicon are each 0.50% min, the copper minimum does not apply.

(g) May be substituted for all or part of V.

(h) Niobium plus vanadium, 0.02 to 0.15%.

(i) Nitrogen with vanadium content of 0.015% (max) with a minimum vanadium-to-nitrogen ratio of 4:1.

(j) When silicon-killed steel is specified.

(k) For plate under 40 mm (1.5 in.), manganese contents are 0.70 to 1.35% or up to 1.60% if carbon equivalents do not exceed 0.47%. For plate thicker than 40 mm (1 to 5 in.), ASTM A 841 specifies manganese contents of 1.00 to 1.60%.

Table 4 Tensile properties of HSLA steel grades specified in ASTM standards

ASTM specification[(a)]	**Type, grade, or condition**	**Product thickness**[(b)]		**Minimum tensile strength**[(c)]		**Minimum yield strength**[(c)]		**Minimum elongation**[(c)]**, %**		Bend radius[(c)]	
		mm	**in.**	**MPa**	**ksi**	**MPa**	**ksi**	**in 200 mm (8 in.)**	**in 50 mm (2 in.)**	**Longitudinal**	Transverse
A 242	Type 1	20	$\frac{3}{4}$	480	70	345	50	18	. . .	. . .	. . .
		20-40	$\frac{3}{4}$-$1\frac{1}{2}$	460	67	315	46	18	21	. . .	. . .
		40-100	$1\frac{1}{2}$-4	435	63	290	42	18	21	. . .	. . .
A 572	Grade 42	150	6	415	60	290	42	20	24	[(d)]	. . .

	Grade 50	100	4	450	65	345	50	18	21	(d)	. . .
	Grade 60	32	$1\frac{1}{4}$	520	75	415	60	16	18	(d)	. . .
	Grade 65	32	$1\frac{1}{4}$	550	80	450	65	15	17	(d)	. . .
A 588	Grades A-K	100	4	485	70	345	50	18	21	(d)	. . .
		100-125	4-5	460	67	315	46	. . .	21	(d)	. . .
		125-200	5-8	435	63	290	42	. . .	21	(d)	. . .
A 606	Hot-rolled	Sheet		480	70	345	50	. . .	22	*t*	**2*t*-3*t***
	Hot-rolled and annealed or normalized	Sheet		450	65	310	45	. . .	22	*t*	**2*t*-3*t***
	Cold-rolled	Sheet		450	65	310	45	. . .	22	*t*	**2*t*-3*t***
A 607	Grade 45	Sheet		410	60	310	45	. . .	22-25	*t*	**1.5*t***
	Grade 50	Sheet		450	65	345	50	. . .	20-22	*t*	**1.5*t***
	Grade 55	Sheet		480	70	380	55	. . .	18-20	1.5*t*	**2*t***
	Grade 60	Sheet		520	75	415	60	. . .	16-18	2*t*	**3*t***
	Grade 65	Sheet		550	80	450	65	. . .	15-16	2.5*t*	**3.5*t***
	Grade 70	Sheet		590	85	485	70	. . .	14	3*t*	**4*t***
A 618	Ia, Ib, II	19	$\frac{3}{4}$	485	70	345	50	19	22	*t*-2*t*	. . .
	Ia, Ib, II, III	19-38	$\frac{3}{4}$-$1\frac{1}{2}$	460	67	315	46	18	22	*t*-2*t*	. . .
A 633	A	100	4	430-570	63-83	290	42	18	23	(d)	. . .

	C, D	65	$2\frac{1}{2}$	485-620	70-90	345	50	18	23	(d)	**. . .**
	C, D	65-100	$2\frac{1}{2}$ - 4	450-590	65-85	315	46	18	23	(d)	**. . .**
	E	100	4	550-690	80-100	415	60	18	23	(d)	**. . .**
	E	100-150	4-6	515-655	75-95	380	55	18	23	(d)	**. . .**
A 656	50	50	2	415	60	345	50	20	. . .	(d)	**. . .**
	60	40	$1\frac{1}{2}$	485	70	415	60	17	. . .	(d)	**. . .**
	70	25	1	550	80	485	70	14	. . .	(d)	**. . .**
	80	20	$\frac{3}{4}$	620	90	550	80	12	. . .	(d)	**. . .**
A 690	. . .	100	4	485	70	345	50	18	. . .	2*t*	**. . .**
A 709	50	100	4	450	65	345	50	18	21	. . .	**. . .**
	50W	100	4	485	70	345	50	18	21	. . .	**. . .**
A 715	Grade 50	Sheet		415	60	345	50	. . .	22-24	0	***t***
	Grade 60	Sheet		485	70	415	60	. . .	20-22	0	***t***
	Grade 70	Sheet		550	80	485	70	. . .	18-20	*t*	**1.5*t***
	Grade 80	Sheet		620	90	550	80	. . .	16-18	*t*	**1.5*t***
A 808	. . .	40	$1\frac{1}{2}$	450	65	345	50	18	22	. . .	**. . .**
		40-50	$1\frac{1}{2}$ - 2	450	65	315	46	18	22	. . .	**. . .**
		50-65	2-	415	60	290	42	18	22	. . .	**. . .**

			$2\frac{1}{2}$								
A 812	65	Sheet		585	85	450	65	. . .	13-15	. . .	. . .
	80	Sheet		690	100	550	80	. . .	11-13	. . .	. . .
A 841	. . .	65	2.5	485-620	70-90	345	50	18	22	. . .	. . .
		65-100	2.5-4	450-585	65-85	310	45	18	22	. . .	. . .
A 871	60, as-hot-rolled	5-35	$\frac{3}{16}$-$1\frac{3}{8}$	520	75	415	60	16	18	. . .	. . .
	65, as-hot-rolled	**5-20**	$\frac{3}{16}$-$\frac{3}{4}$	**550**	**80**	**450**	**65**	**15**	**17**	**. . .**	. . .

(a) For characteristics and intended uses, see Table 2; for specified compositional limits, see Table 3.

(b) Maximum product thickness except when a range is given. No thicknesses are specified for sheet products.

(c) May vary with product size and mill form.

(d) Optional supplementary requirement given in ASTM A 6

Heat Treated Structural Low-Alloy Grades

Heat treated structural low-alloy grades have better hardenability than carbon grades and thus can provide both high strength and good toughness in thicker sections. Their alloy content provides improved heat and corrosion resistance. However, these grades are somewhat more difficult to weld and generally are more expensive than carbon or HSLA grades. Quenched-and-tempered low-alloy grades may be ordered to fulfill the requirements of ASTM A 514 or A 517. The properties required of these steels are produced by heating to at least 900 °C (1650 °F), quenching in water or oil, and tempering at not less than 600 °C (1100 °F) to provide microstructures of tempered martensite or tempered martensite plus bainite, depending on section thickness.

Steels in this category typically contain less than 0.25% C and less than 5% alloy content. Yield strength values range from approximately 345 to 895 MPa (50 to 130 ksi), and tensile strength values range from 485 to 1035 MPa (70 to 150 ksi), depending on chemical composition, thickness, and heat treatment. Table 5 lists minimum tensile requirements for low-carbon quenched-and-tempered steels. These steels are furnished primarily as plate, although some are produced as either forgings or castings.

Table 5 Minimum tensile properties and maximum plate thickness for quenched and tempered low-alloy steels

Specification or common designation	**Grade, type, or class**	**Plate thickness**[a]		**Minimum yield strength**		**Tensile strength**		Minimum elongation in 50 mm (2 in.), %
		mm	**in.**	**MPa**	**ksi**	**MPa**	**ksi**	
ASTM A 514 or A 517	A, B, C	32	$1\frac{1}{4}$	690	100	760-895	110-130	**18**
	E, F	65	$2\frac{1}{2}$	690	100	760-895	110-130	**18**
	E	65-150	$2\frac{1}{2}$-6	620	90	690-895	100-130	**16**
ASTM A 533	Class 1 (type A, B, or C)	300	12	345	50	550-690	80-100	**18**
	Class 2 (type A, B, or C)	300	12	485	70	620-795	90-115	**16**
	Class 3 (type A, B, or C)	65	$2\frac{1}{2}$	570	83	690-860	100-125	**16**
ASTM A 543	B, C	[b]	[b]	485-585	70-85	620-930	90-135	**14-16**
ASTM A 678	D	75	3	515	75	620-760	90-110	**18**
ASTM A 709	70W	100	4	425	70	620-760	90-110	**19**
	100, 100W	65	$2\frac{1}{2}$	690	100	760-895	110-130	**18**
	100, 100W	**65-100**	**$2\frac{1}{2}$-4**	**620**	**90**	**690-895**	**100-130**	**16**

Compositions for these steels are provided in the article "Classifications and Designations for Carbon and Alloy Steels" in this Section

(a) Maximum plate thickness for the specified mechanical properties when a single value is shown.

(b) Maximum plate thickness is not defined in ASTM A 543; plates in ASTM A 543 are intended for applications requiring plate thicknesses of 50 mm (2 in.) or more.

Ultrahigh-Strength Steels

Introduction

ULTRAHIGH-STRENGTH STEELS are designed to be used in structural applications where very high loads are applied and often where high strength-to-weight ratios are required. In addition, they must also possess good ductility and toughness. The latter properties have been historically measured by tensile ductility, namely, percent elongation and reduction of area, and by impact resistance or energy absorbed in a notched impact test. However, in recent years the property of fracture toughness has become a significant factor in the acceptance of steels for critical high-performance structural applications.

The designation ultrahigh-strength is arbitrary because no universally accepted strength level for the term has been established. Also, as structural steels with greater and greater strength have been developed, the strength range for which the term is applied has gradually increased. This article describes those commercial structural steels capable of a minimum yield strength of 1380 MPa (200 ksi).

In addition to the steels discussed in this article, many other proprietary and standard steels are used for essentially the same types of applications, but at strength levels slightly below the arbitrary, lower limit of 1380 MPa (200 ksi) established above for the ultrahigh-strength class of constructional steels. Medium-alloy steels such as 4330V and 4335V (vanadium-modified versions of the corresponding SAE-AISI standard steels) are among the more widely used steels for yield strengths of 1240 to 1380 MPa (180 to 200 ksi). Certain proprietary steels such as Hy Tuf (a silicon-modified steel similar to 300M) exhibit excellent toughness at strengths up to or slightly above 1380 MPa. The toughness of Hy Tuf is about the same as a maraging steel in this strength range. For properties and other information on steels and strength ranges not discussed here, the reader is referred to sources such as *Aerospace Structural Metals Handbook,* published by the Mechanical Properties Data Center, Battelle Laboratories (Columbus, OH), and to producer data sheets.

The ultrahigh-strength class of constructional steels is quite broad and includes a number of distinctly different families of steels. However, in order to simplify the approach to understanding these alloys, this article divides them into four categories:

- Medium-carbon low-alloy steels
- Medium-alloy air-hardening steels
- High fracture toughness steels
- Maraging steels

Additional information on these steels, specifically, recommended heat treatments, can be found in the Section "Heat Treating" in this Handbook.

Medium-Carbon Low-Alloy Steels

The medium-carbon low-alloy family of ultrahigh-strength steels includes SAE-AISI 4130, the higher-strength 4140, and the deeper hardening, higher-strength 4340. Several modifications of the basic 4340 steel have been developed. In one modification (300M), silicon content is increased to prevent embrittlement when the steel is tempered at the low temperatures required for very high strength. In AMS 6434, vanadium is added as a grain refiner to increase toughness, and the carbon is slightly reduced to promote weldability. Ladish D-6a contains the grain refiner vanadium; slightly higher carbon, chromium, and molybdenum than 4340; and slightly lower nickel. Other less widely used steels that may be included in this family are 6150 and 8640. Chemical compositions are given in Table 1. Property data on 4340, 300M, and D-6a are given below. Property data on the other SAE-AISI grades listed in Table 1 can be found in the article "Mechanical Properties of Carbon and Alloy Steels" in this Section.

Table 1 Compositions of ultrahigh-strength steels

Designation or trade name[(a)]	Composition[(b)], wt%							
	C	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**V**	Cr
Medium-carbon low-alloy steels								
4130	0.28-0.33	0.40-0.60	0.20-0.35	0.80-1.10	. . .	0.15-0.25	. . .	**. . .**
4140	0.38-0.43	0.75-1.00	0.20-0.35	0.80-1.10	. . .	0.15-0.25	. . .	**. . .**
4340	0.38-0.43	0.60-0.80	0.20-0.35	0.70-0.90	1.65-2.00	0.20-0.30	. . .	**. . .**
AMS 6434	0.31-0.38	0.60-0.80	0.20-0.35	0.65-0.90	1.65-2.00	0.30-0.40	0.17-0.23	**. . .**
300M	0.40-0.46	0.65-0.90	1.45-1.80	0.70-0.95	1.65-2.00	0.30-0.45	0.05 min	**. . .**
D-6a	0.42-0.48	0.60-0.90	0.15-0.30	0.90-1.20	0.40-0.70	0.90-1.10	0.05-0.10	**. . .**
6150	0.48-0.53	0.70-0.90	0.20-0.35	0.80-1.10	. . .	. . .	0.15-0.25	**. . .**
8640	0.38-0.43	0.75-1.00	0.20-0.35	0.40-0.60	0.40-0.70	0.15-0.25	. . .	**. . .**
Medium-alloy air-hardening steels								
H11 mod	0.37-0.43	0.20-0.40	0.80-1.00	4.75-5.25	. . .	1.20-1.40	0.40-0.60	**. . .**
H13	0.32-0.45	0.20-0.50	0.80-1.20	4.75-5.50	. . .	1.10-1.75	0.80-1.20	**. . .**
High fracture toughness steels								
AF1410[(c)]	0.13-0.17	0.10 max	0.10 max	1.80-2.20	9.50-10.50	0.90-1.10	. . .	**13.50-14.50**
HP-9-4-30[(d)]	0.29-0.34	0.10-0.35	0.20 max	0.90-1.10	7.0-8.0	0.90-1.10	0.06-0.12	**4.25-4.75**

(a) The compositions of the ultrahigh-strength maraging steels described in this article are listed in Table 9.

(b) P and S contents may vary with steelmaking practice. Usually, these steels contain no more than

0.035 P and 0.040 S.

(c) AF1410 is specified to have 0.008 P and 0.005 S composition. Ranges utilized by some producers are narrower.

(d) HP-9-4-30 is specified to have 0.10 max P and 0.10 max S. Ranges utilized by some producers are narrower.

No new or distinctly different commercial steels have been added to this class of steels in recent years. Rather, developmental efforts have been primarily aimed at increasing ductility and toughness by improving melting and processing techniques and by using stricter process control and inspection. Steels with fewer and smaller nonmetallic inclusions and mill products with fewer internal and surface imperfections are produced by the use of selected raw materials as the melting charge and the employment of advanced melting techniques such as vacuum carbon deoxidation, vacuum degassing, electroslag remelting (ESR), vacuum arc remelting (VAR), and double vacuum melting (vacuum induction melting followed by vacuum arc remelting, or VIM/VAR). These techniques yield less variation in properties from heat to heat and lot to lot; greater ductility and toughness, especially in the transverse direction; and greater in-service reliability.

4340 Steel

SAE-AISI 4340 steel is considered the standard by which other ultrahigh-strength steels are compared. It combines deep hardenability with high ductility, toughness, and strength. It has high fatigue and creep resistance. It is often used where severe service conditions exist and where high strength in heavy sections is required. In thin sections, this steel is air hardening; in practice, it is usually oil quenched. It is especially immune to temper embrittlement. It does not soften readily at elevated temperatures; that is, it exhibits good retention of strength. Hydrogen embrittlement is a problem for 4340 heat treated to tensile strengths greater than about 1400 MPa (200 ksi). Parts exposed to hydrogen, such as during pickling and plating, should be baked subsequently. This steel exhibits extremely poor resistance to stress-corrosion cracking when tempered to tensile strengths of 1500 to 1950 MPa (220 to 280 ksi). It can be readily nitrided, which often improves fatigue life.

Processing. The 4340 steel is usually forged at 1065 to 1230 °C (1950 to 2250 °F); after forging, parts may be air cooled in a dry place or, preferably, furnace cooled. The machinability rating of 4340 is 55% for cold-drawn material, and 45% for annealed material (cold-rolled B1112, 100%). A partly spheroidized structure obtained by normalizing and then tempering at 650 °C (1200 °F) is best for optimum machinability. The 4340 steel has good welding characteristics. It can be readily gas or arc welded, but welding rods of the same composition should be used. Because 4340 is air hardening, welded parts should be either annealed or normalized and tempered shortly after welding.

Product Forms and Applications. The steel 4340 is widely and readily available as billet, bar, rod, forgings, sheet, tubing, and welding wire. It is also produced as light plate and castings. Typical applications include bolts, screws, and other fasteners; gears, pinions, shafts, and similar machinery components; crankshafts and piston rods for engines; and landing gear and other critical structural members for aircraft.

Properties. Through-hardening of 4340 steel can be done by oil quenching, for round sections up to 75 mm (3 in.) in diameter, and by water quenching, for larger sections (up to the limit of hardenability). Typical mechanical properties of oil-quenched 4340 are given in Table 2.

Table 2 Typical mechanical properties of 4340 steel

Tempering temperature		**Tensile strength**		**Yield strength**		**Elongation in 50 mm (2 in.), %**	**Reduction in area, %**	**Hardness**		Izod impact energy	
°C	**°F**	**MPa**	**ksi**	**MPa**	**ksi**			**HB**	**HRC**	**J**	ft · lbf
205	400	1980	287	1860	270	11	39	520	53	20	**15**
315	600	1760	255	1620	235	12	44	490	49.5	14	**10**
425	800	1500	217	1365	198	14	48	440	46	16	**12**
540	1000	1240	180	1160	168	17	53	360	39	47	**35**
650	1200	1020	148	860	125	20	60	290	31	100	**74**
705	**1300**	**860**	**125**	**740**	**108**	**23**	**63**	**250**	**24**	**102**	**75**

300M Steel

Alloy 300M is basically a silicon-modified (1.6% Si) 4340 steel, but it has slightly higher carbon and molybdenum contents and also contains vanadium. This steel exhibits deep hardenability and has ductility and toughness at tensile strengths of 1860 to 2070 MPa (270 to 300 ksi). Many of the properties of this steel are similar to those of 4340 steel, except that the increased silicon content provides deeper hardenability, increased solid-solution strengthening, and better resistance to softening at elevated temperatures. Compared to 4340 of similar strength, 300M can be tempered at a higher temperature, which provides greater relief of quenching stresses. The so-called 260 °C (500 °F) embrittlement is displaced to higher temperatures. Because of the high silicon and molybdenum contents, 300M is particularly prone to decarburization. During thermal processing, care should be exercised to avoid decarburization, or the decarburized layer should be removed after processing. When heat treated to strength levels higher than 1380 MPa (200 ksi) 300M is susceptible to hydrogen embrittlement. If the steel is properly baked after plating, the resulting improvement in properties is better than that for 4340 or D-6ac steel of equal strength.

Processing. The steel 300M is forged at 1065 to 1095 °C (1950 to 2000 °F). Forging should not be continued below 925 °C (1700 °F). After forging, it is preferred that parts be slowly cooled in a furnace, but they may be allowed to cool in air in a dry place. Although 300M can be readily gas or arc welded, welding is generally not recommended; welding rod of the same composition should be used. Because 300M is an air-hardening steel, parts should be either annealed or normalized and tempered after welding. The machinability rating of annealed 300M is about 45% (B1112, 100%). A partially spheroidized structure, obtained by normalizing and then tempering at 650 to 675 °C (1200 to 1250 °F), gives optimum machinability.

Product Forms and Applications. Typical applications of 300M, which is available as bar, sheet, plate, wire, tubing, forgings, and castings, are aircraft landing gear, airframe parts, fasteners, and pressure vessels.

Properties. Variations in hardness and mechanical properties of 300M with tempering temperature are presented in Table 3.

Table 3 Typical mechanical properties of 300M steel

Tempering temperature		**Tensile strength**		**Yield strength**		**Elongation in 50 mm (2 in.), %**	**Reduction in area, %**	**Charpy V-notch impact energy**		Hardness, HRC
°C	**°F**	**MPa**	**ksi**	**MPa**	**ksi**			**J**	**ft · lbf**	
90	200	2340	340	1240	180	6.0	10.0	17.6	13.0	**56.0**
205	400	2140	310	1650	240	7.0	27.0	21.7	16.0	**54.5**
260	500	2050	297	1670	242	8.0	32.0	24.4	18.0	**54.0**
315	600	1990	289	1690	245	9.5	34.0	29.8	22.0	**53.0**
370	700	1930	280	1620	235	9.0	32.0	23.7	17.5	**51.0**
425	**800**	**1790**	**260**	**1480**	**215**	**8.5**	**23.0**	**13.6**	**10.0**	**45.5**

D-6a and D-6ac Steel

Ladish D-6a is a low-alloy ultrahigh-strength steel developed for aircraft and missile structural applications. It is designed primarily for use at room-temperature tensile strengths of 1800 to 2000 MPa (260 to 290 ksi). The steel D-6a maintains a very high ratio of yield strength to tensile strength up to a tensile strength of 1930 MPa (280 ksi), combined with good ductility. It, has good notch toughness, which results in high resistance to impact loading. It is deeper hardening than 4340 and does not exhibit temper embrittlement. It retains high strength at elevated temperature. Susceptibility of D-6a to stress-corrosion cracking and corrosion fatigue in moist and aqueous environments is comparable to that of 300M steel at the same strength level. The alloy is called D-6a when produced by air melting in an electric furnace and D-6ac when produced by air melting followed by vacuum arc remelting. The mechanical properties of D-6a and D-6ac differ somewhat as a result of the differences in melting practices. Other characteristics of the two steels, including processing behavior, are identical.

Processing. To forge D-6a, it should be heated to a maximum temperature of 1230 °C (2250 °F); forging should be finished above 980 °C (1800 °F). Finished forgings should be cooled slowly, either in a furnace or embedded in a suitable insulating medium such as ashes or lime. For maximum machinability, the parts should be charged into a 650 °C (1200 °F) furnace immediately after forging and held for 12 h; temperature should be increased to 900 °C (1650 °F) and held for a time period that depends on section size; parts should be cooled to 650 °C (1200 °F), held 10 h, and finally air cooled to room temperature.

The material D-6a, even in heavy sections, can be welded provided that the techniques and controls normally employed for welding medium-carbon, high hardenability alloy steels are used. Welding rod of the same composition should be used.

Annealed D-6a has a machinability rating of 50 to 55% (B1112, 100%). When the steel is to be severely cold formed, it is usually normalized and then spheroidized before working.

Product Forms and Applications. D-6a and D-6ac are available as bar, rod, billet, and forgings and can be made as flat-rolled products (sheet and plate) as well. These forms are used in landing gear and critical structural components for aircraft, motor cases for solid-fuel rockets, shafts, gears, springs, dies, dummy blocks, and backer blocks.

Properties. Typical mechanical properties of heat treated D-6a bar are given in Table 4.

Table 4 Typical mechanical properties of D-6a steel bar

Tempering temperature		**Tensile strength**		**Yield strength**		**Elongation in 50 mm (2 in.), %**	**Reduction in area, %**	Charpy V-notch impact energy	
°C	**°F**	**MPa**	**ksi**	**MPa**	**ksi**			**J**	ft · lbf
150	300	2060	299	1450	211	8.5	19.0	14	**10**
205	400	2000	290	1620	235	8.9	25.7	15	**11**
315	600	1840	267	1700	247	8.1	30.0	16	**12**
425	800	1630	236	1570	228	9.6	36.8	16	**12**
540	1000	1450	210	1410	204	13.0	45.5	26	**19**
650	**1200**	**1030**	**150**	**970**	**141**	**18.4**	**60.8**	**41**	**30**

Medium-Alloy Air-Hardening Steels

The ultrahigh-strength steels H11 modified (H11 mod) and H13, which are popularly known as 5% Cr hot-work die steels, are discussed in this section. Besides being extensively used in dies, these steels are widely used for structural applications, but not as widely as they once were, primarily because of the development of several other steels at essentially the same cost but with substantially greater fracture toughness at equivalent strength. Nonetheless, H11 mod and H13 possess some attractive features. Both can be hardened through in large sections by air cooling. The chemical compositions of these steels are given in Table 1.

H11 Modified

This steel is a modification of the martensitic hot-work die steel AISI H11, the significant difference being a slightly higher carbon content. The H11 mod steel can be heat treated to strengths exceeding 2070 MPa (300 ksi). It is air hardened, which results in minimal residual stress after hardening. Because H11 mod is a secondary hardening steel, it develops optimum properties when tempered at temperatures above 510 °C (950 °F). The high tempering temperatures used for this steel provide substantial stress relief and stabilization of properties so that the material can be used to advantage at elevated temperatures.

Processing. The material H11 mod is readily forged from 1120 to 1150 °C (2050 to 2100 °F). Preferably, stock should be preheated at 790 to 815 °C (1450 to 1500 °F) and then heated uniformly to the forging temperature. Forging should not be continued below 925 °C (1700 °F). Stock may be reheated as often as necessary. Because H11 mod is air hardening, it must be cooled slowly after forging to prevent stress cracks. After forging, the part should be charged into a furnace at about 790 °C (1450 °F); soaked until the temperature is uniform; and then slowly cooled, either while retained in the furnace or buried in an insulating medium such as lime, mica, or a siliceous filler material such as silocel. When the forging has cooled, it should be annealed.

The steel H11 mod, even in heavy sections, is readily welded. Fusion welding generally is accomplished with an inert-gas process or with coated electrodes. Filler metal should be of the same general composition. The machinability rating for H11 mod is about 60% of the rating for 1% C steel, or about 45% of that for B 1112.

Product Forms and Applications. The H11 mod steel is available as bar, billet, rod, wire, plate, sheet, strip, forgings, and extrusions. It is used for parts requiring high strength combined with either strength retention at elevated temperatures or moderate corrosion resistance. Typical applications include aircraft landing gear components, airframe components, internal parts for steam and gas turbines, fasteners, springs, and hot-work dies.

Properties. Typical longitudinal mechanical properties of H11 Mod after heat treatment are presented in Table 5.

Table 5 Typical longitudinal mechanical properties of H11 mod steel

Tempering temperature		**Tensile strength**		**Yield strength**		**Elongation in 50 mm (2 in.), %**	**Reduction in area, %**	**Charpy V-notch impact energy**		Hardness, HRC
°C	**°F**	**MPa**	**ksi**	**MPa**	**ksi**			**J**	**ft · lbf**	
510	950	2120	308	1710	248	5.9	29.5	13.6	10.0	**56.5**
540	1000	2005	291	1675	243	9.6	30.6	21.0	15.5	**56.0**
565	1050	1855	269	1565	227	11.0	34.5	26.4	19.5	**52.0**
595	1100	1540	223	1320	192	13.1	39.3	31.2	23.0	**45.0**
650	1200	1060	154	855	124	14.1	41.2	40.0	29.5	**33.0**
705	**1300**	**940**	**136**	**700**	**101**	**16.4**	**42.2**	**90.6**	**66.8**	**29.0**

H13 Steel

AISI H13 is a 5% Cr ultrahigh-strength steel similar to H11 mod in composition, heat treatment, and many properties. The main difference in composition is the higher vanadium content of H13 (see Table 1); this leads to a greater dispersion of hard vanadium carbides, which results in higher wear resistance.

Like H11 mod, H13 is a secondary-hardening steel. It has good temper resistance and maintains high hardness and strength at elevated temperatures. It is deep hardening, which allows large sections to be hardened by air cooling. H13 steel can be heat treated to strengths exceeding 2070 MPa (300 ksi); like H11 mod, it has good ductility and impact strength. Processing procedures for H13 are almost identical to those outlined above for H11 mod.

High Fracture Toughness Steels

High-strength, high fracture toughness steels as described in this article are commercial structural steels capable of a yield strength of 1380 MPa (200 ksi) and a K_{Ic} of 100 MPa$\sqrt{m}$ (91 ksi$\sqrt{in.}$). These steels also exhibit stress corrosion cracking resistance.

Three steels are considered here; HP-9-4-30, AF1410, and AerMet100. These alloys are of the Ni-Co-Fe type. They have a number of similar characteristics. They are all weldable. They all require a minimum of vacuum arc melting and control of residual elements to low levels to obtain maximum toughness.

HP-9-4-30 Steel

During the 1960s, Republic Steel Corporation introduced a family of four weldable steels, all of which had high fracture toughness when heat treated to medium/high strength levels. Only HP-9-4-30 has been produced in significant quantities and is comparable to the high-strength, high fracture toughness steels of this article. The chemical composition is given in Table 1. The HP-9-4-30 steel is usually electric arc melted and then vacuum arc remelted. Forging temperatures should not exceed 1120 °C (2050 °F). The HP-9-4-30 steel is capable of developing a tensile strength of 1520 to 1650 MPa (220 to 240 ksi) with a plain-strain fracture toughness of 100 MPa$\sqrt{\text{m}}$ (91 ksi$\sqrt{\text{in.}}$). This steel has deep hardenability and can be fully hardened to martensite in sections up to 150 mm (6 in.) thick. The HP-9-4-30 steel in the heat-treated condition can be formed by bending, rolling, or shear spinning. Heat-treated parts can readily be welded. Tungsten arc welding under inert-gas shielding is the preferred welding process. Neither postheating nor postweld heat treating is required. After welding, parts may be stress relieved at about 540 °C (1000 °F) for 24 h. This is a stress-relieving treatment and has no adverse effect on the strength or toughness of either the weld metal or the base metal. The HP-9-4-30 steel is available as billet, bar, rod, plate, sheet, and strip. It has been used for aircraft structural components, pressure vessels, rotor shafts for metal forming equipment, drop hammer rods, and high-strength shock-absorbing automotive parts.

Properties. Table 6 presents room-temperature mechanical properties of HP-9-4-30 double tempered at three different temperatures.

Table 6 Room-temperature mechanical properties of HP-9-4-30 steel

Property	Typical value for hardness of		
	49-53 HRC[(a)]	**44-48 HRC**[(b)]	Minimum value[(c)]
Tensile strength, MPa (ksi)	1650-1790 (240-260)	1520-1650 (220-240)	**1520 (220)**
Yield strength, MPa (ksi)	1380-1450 (200-210)	1310-1380 (190-200)	**1310 (190)**
Elongation in 4*D* gage length, %	8-12	12-16	**10**
Reduction in area, %	25-35	35-50	**35**
Charpy V-notch impact energy, J (ft · lbf)	20-27 (15-20)	24-34 (18-25)	**24 (18)**

(a) Oil quenched from 845 °C (1550 °F), refrigerated to -73 °C (-100 °F) and double tempered at 205 °C (400 °F).

(b) Same heat treatment as (a) except double tempered at 550 °C (1025 °F).

(c) For sections forged to 75 mm (3 in.) or less in thickness (or to less than 0.016 m^2, or 25 $in.^2$, in total cross-sectional area), quenched to martensite and double tempered at 540 °C (1000 °F)

AF1410 Steel

The steel AF1410 was an outgrowth of the U.S. Air Force sponsorship of the advanced submarine hull steels, the result of which was the development of the low-carbon Fe-Ni-Co type alloys. These alloys had significant stress corrosion cracking resistance. By raising the cobalt and carbon content, the ultimate tensile strength was increased to a typical 1615

MPa (235 ksi). This increase in strength was obtained while maintaining a K_{Ic} value of 154 MPa $\sqrt{m}$(140 ksi $\sqrt{in.}$). This combination of strength and toughness exceeds that of other commercially available steels, and the alloy has been considered as a replacement for titanium in certain aircraft parts. The AF1410 material (see Table 1 for composition) is air hardenable in sections up to 75 mm (3 in.) thick. The preferred melting practice is presently vacuum induction melting followed by vacuum arc remelting (VIM/VAR). However, initially VIM and VIM/ESR practices were used. Melting practice requires that impurity elements be kept at very low levels, to ensure high fracture toughness. Although forgeable to 1120 °C (2050 °F), at least a 40% reduction must be obtained below 900 °C (1650 °F) to attain maximum properties. Weldability is good using a continuous wave (CW)-gas tungsten arc welding (GTAW) process, provided that high-purity wire is used and oxygen contamination is avoided. Obtainable as bar, billet, rod, plate, sheet, and strip; AF1410 has been used for aircraft structural components.

Properties. The effects of various quenching media on the tensile properties, impact strength, and fracture toughness of AF1410 are shown in Table 7.

Table 7 Mechanical properties of a AF1410 steel quenched in various media

Quench medium	**Ultimate strength**		**Yield strength**		**Elongation, %**	**Reduction in area, %**	**Charpy V-notch**		Plane-strain fracture toughness (K_{Ic})	
	MPa	**ksi**	**MPa**	**ksi**			**J**	**ft · lbf**	**MPa** $\sqrt{m}$	ksi $\sqrt{in}$
Air	1680	244	1475	214	16	69	69	51	174	**158**
Oil	1750	254	1545	224	16	69	65	48	154	**140**
Water	**1710**	**248**	**1570**	**228**	**16**	**70**	**65**	**48**	**160**	**146**

Test specimens were 50 mm (2 in.) plate from VIM/VAR melt with the heat treatment: 675 °C (1250 °F) for 8 h with air cooling, 900 °C (1650 °F) for 1 h, quenching, 830 °C (1525 °F) for 1 h, quenching, refrigeration at -73 °C (-100 °F) for 1 h, 510 °C (950 °F) for 5

AerMet 100 Steel

AerMet 100 steel is the most recently developed (patented in 1991) high-strength nickel-cobalt steel developed for the aircraft and aerospace industries. It is supplied only in the VIM/VAR melted condition. Table 1 lists the composition of AerMet 100, which can be heat treated to 1930 to 2070 MPa (280 to 300 ksi) tensile strength, while exhibiting fracture toughness exceeding 110 MPa$\sqrt{m}$ at 1930 MPa (100 ksi$\sqrt{in.}$ at 280 ksi). In addition, it offers exceptional resistance to stress-corrosion cracking and fatigue compared with other steels. Like other medium-carbon ultrahigh-strength steels, AerMet 100 is subject to decarburization, and heat treatment should be conducted in a neutral atmosphere furnace, salt bath, or in vacuum. AerMet 100 is available as solid bar, hollow bar, wire, strip, billet, sheet, and plate. These product forms can be used in landing-gear components, arresting hooks, catapult hooks, fasteners, structural members, armor, actuators, ordnance, ballistic-tolerant components, jet engine shafts, drive shafts, helicopter masts, and containment rings.

Properties. Typical mechanical properties of AerMet 100 are listed in Table 8.

Table 8 Typical mechanical properties of AerMet 100 steel

Yield strength		**Ultimate tensile strength**		**Elongation, %**	**Reduction of area, %**	**Charpy V-notch impact energy**		Fracture toughness (K_{Ic})	
MPa	**ksi**	**MPa**	**ksi**			**J**	**ft · lbf**	**MPa**$\sqrt{\mathrm{m}}$	ksi$\sqrt{\mathrm{in.}}$
Longitudinal orientation									
1724	250	1965	285	14	65	41	30	126	**115**
Transverse orientation									
1724	**250**	**1965**	**285**	**13**	**55**	**34**	**25**	**110**	**100**

Solution heat treated at 885 °C (1625 °F) for 1 h, air cooled, refrigerated at -73 °C (-100 °F) for 1 h, and aged at 480 °C (900 °F) for 5

Maraging Steels

Maraging steels comprise a special class of ultrahigh-strength steels that differ from conventional steels in that they are hardened by a metallurgical reaction that does not involve carbon. Instead, these steels are strengthened by the precipitation of intermetallic compounds at temperatures of about 480 °C (900 °F). The term maraging is derived from martensite age hardening and denotes the age hardening of a low-carbon, iron-nickel lath martensite matrix.

Commercial maraging steels are designed to provide specific levels of yield strength from 1030 to 2420 MPa (150 to 350 ksi). Some experimental maraging steel have yield strengths as high as 3450 MPa (500 ksi). These steels typically have very high nickel, cobalt, and molybdenum contents and very low carbon contents. Carbon, in fact, is an impurity in these steels and is kept as low as commercially feasible in order to minimize the formation of titanium carbide (TiC), which can adversely affect strength, ductility, and toughness.

Physical Metallurgy

Maraging steels can be considered highly alloyed low-carbon, iron-nickel lath martensites. The phase transformations in these steels can be explained with the help of the two phase diagrams shown in Fig. 1, which depict the iron-rich end of the Fe-Ni binary system. Figure 1(a) is the metastable diagram plotting the austenite-to-martensite transformation upon cooling and the martensite-to-austenite reversion upon heating. Figure 1(b) is the equilibrium diagram showing that at higher nickel contents the equilibrium phases at low temperatures are austenite and ferrite.

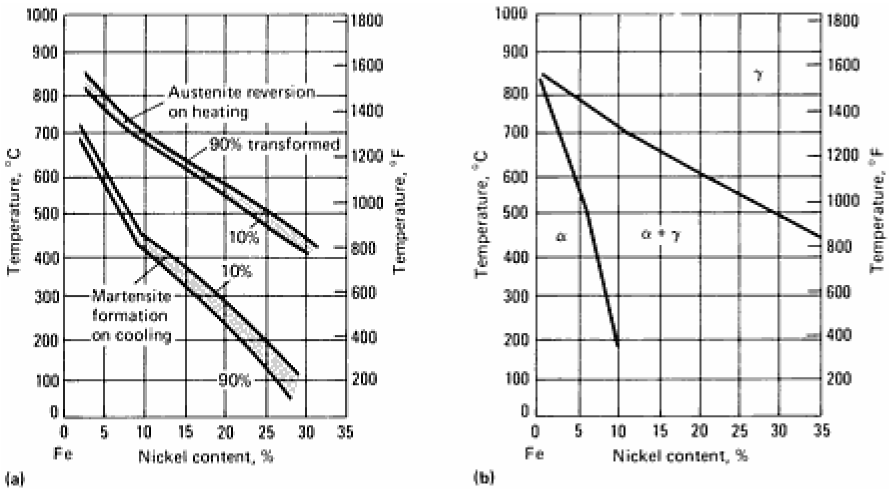


Fig. 1 Phase relationships in the iron-nickel system. (a) Metastable. (b) Equilibrium

The age hardening of maraging steels is produced by heat treating for 3 to 9 h at temperatures of the order of 455 to 510 °C (850 to 950 °F). The metallurgical reactions that take place during such treatment can be explained by using the equilibrium diagram (Fig. 1b).

Commercial Alloys

Table 9 lists the chemical compositions of the more common grades of maraging steel. The nomenclature that has become established for these steels is nominal yield strength (ksi units) in parentheses. Thus, for example, 18Ni(200) steel is normally age hardened to a yield strength of 1380 MPa (200 ksi). The first three steels in Table 9--18Ni(200), 18Ni(250), and 18Ni(300)--are the most widely used and most commonly available grades. The 18Ni(350) grade is an ultrahigh-strength variety made in limited quantities for special applications. Two 18Ni(350) compositions have been produced (see the footnote in Table 9). The 18Ni(Cast) grade was developed specifically as a cast composition.

Table 9 Nominal compositions of commercial maraging steels

Grade	Composition(a), %					
	Ni	**Mo**	**Co**	**Ti**	**Al**	Nb
Standard grades						
18Ni(200)	18	3.3	8.5	0.2	0.1	. . .
18Ni(250)	18	5.0	8.5	0.4	0.1	. . .
18Ni(300)	18	5.0	9.0	0.7	0.1	. . .
18Ni(350)	18	4.2(b)	12.5	1.6	0.1	. . .
18Ni(Cast)	17	4.6	10.0	0.3	0.1	. . .

12-5-3(180)(c)	12	3	. . .	0.2	0.3	**. . .**
Cobalt-free and low-cobalt bearing grades						
Cobalt-free 18Ni(200)	18.5	3.0	. . .	0.7	0.1	**. . .**
Cobalt-free 18Ni(250)	18.5	3.0	. . .	1.4	0.1	**. . .**
Low-cobalt 18Ni(250)	18.5	2.6	2.0	1.2	0.1	**0.1**
Cobalt-free 18Ni(300)	**18.5**	**4.0**	**. . .**	**1.85**	**0.1**	**. . .**

(a) All grades contain no more than 0.03% C.

(b) Some producers use a combination of 4.8% Mo and 1.4% Ti, nominal.

(c) Contains 5% Cr

A number of cobalt-free maraging steels and a low-cobalt bearing maraging steel have recently been developed. The driving force for the development of these particular alloys was the cobalt shortage and resultant price escalation of cobalt during the late 1970s and early 1980s. The nominal compositions for these alloys are also listed in Table 9.

Processing

Melting. Most grades of maraging steel are either air melted, then vacuum arc remelted, or vacuum induction melted, then vacuum arc remelted. Premium grades of maraging steels used in critical aircraft and aerospace applications, for which minimum residual element (carbon, manganese, sulfur, and phosphorus) and gas (O_2, N_2, and H_2) contents are required, are triple melted using the air, vacuum induction, and vacuum arc remelting processes.

Hot Working. Maraging steels can be hot worked by conventional steel mill techniques, even though allowances must be made for several unique characteristics. Steels with high titanium contents have greater hot strength than conventional steels and require higher hot-working loads or higher working temperatures. Working above about 1260 °C (2300 °F) should be avoided.

Cold Working. Maraging steels can be cold worked by any conventional technique when in the solution-annealed (unaged or as-transformed) condition. They have very low work-hardening rates and can be subjected to very heavy reductions (>50%) with only slight accompanying gains in hardness.

Machining. Maraging steels can be machined by any conventional technique when in the solution-annealed or age-hardened condition. Machinability is generally as good as or better than that of conventional steels of the same hardness.

Welding. All conventional welding processes have been used for joining maraging steels. Most fabrication has, however, employed inert-gas welding processes. Filler metals of matching composition should be employed.

Mechanical Properties

Typical tensile properties and fracture toughness values of the conventional grades of maraging steel are listed in Table 10. One of the distinguishing features of maraging steels is superior toughness compared to conventional steels. Figure 2 compares K_{Ic} values for several maraging steels with those of quenched and tempered alloy steels as a function of tensile strength. The toughness of maraging steels is sensitive to purity level, and carbon and sulfur levels in particular should be kept low to obtain optimum fracture toughness.

Table 10 Heat treatments and typical mechanical properties of standard 18Ni maraging steels

Grade	**Heat treatment**[(a)]	**Tensile strength**		**Yield strength**		**Elongation in 50 mm (2 in.), %**	**Reduction in area, %**	Fracture toughness	
		MPa	**ksi**	**MPa**	**ksi**			**MPa**$\sqrt{m}$	ksi$\sqrt{in}$
18Ni(200)	A	1500	218	1400	203	10	60	155-240	**140-220**
18Ni(250)	A	1800	260	1700	247	8	55	120	**110**
18Ni(300)	A	2050	297	2000	290	7	40	80	**73**
18Ni(350)	B	2450	355	2400	348	6	25	35-50	**32-45**

(a) Treatment A: solution treat 1 h at 820 °C (1500 °F), then age 3 h at 480 °C (900 °F); treatment B: solution treat 1 h at 820 °C (1500 °F), then age 12 h at 480 °C (900 °F); treatment C: anneal 1 h at 1150 °C (2100 °F), age 1 h at 595 °C (1100 °F), solution treat 1 h at 820 °C (1500 °F), and age 3 h at 480 °C (900 °F)

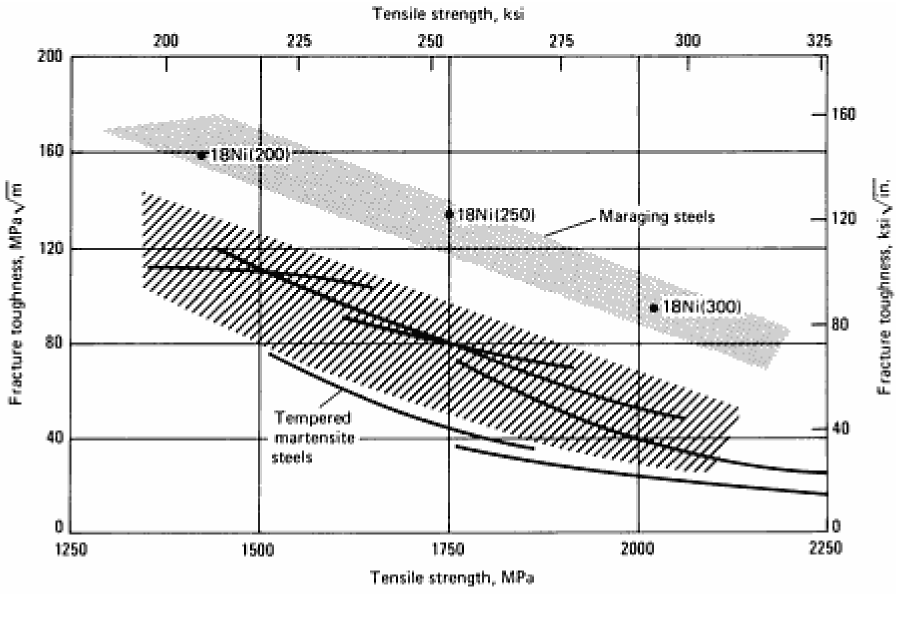


Fig. 2 Plane-strain fracture toughness of maraging steels compared with fracture toughness of several ultrahigh-strength steels as a function of tensile strength

Comparative Data for Ultrahigh-Strength Steels

The choice of an ultrahigh-strength steel for a particular application is dependent on many factors. They constitute not only strength and toughness, but also those requirements dictated by environment, such as temperature and corrosion or resistance to stress-corrosion cracking. In addition to these, commercial factors of availability and cost are significant in the final selection of a steel.

To assist the designer in selecting the optimum grade of ultrahigh-strength steels, data have been generated which compare the four classes of steels described in this article. Examples of these comparative data are shown in Fig. 3 and 4. Standard or producer recommended heat treatments were utilized. As these data indicate, the older, more established medium-carbon low-alloy steels and the medium-alloy air-hardening steels have comparable yield strength values when compared with the high fracture toughness steels and maraging steels. However, the toughness, fatigue strength (not shown in Fig. 3 and 4), and resistance to stress-corrosion cracking are much greater for the nickel-cobalt steels and maraging steels. These more highly alloyed steels are, however, much more expensive and their availability is sometimes limited.

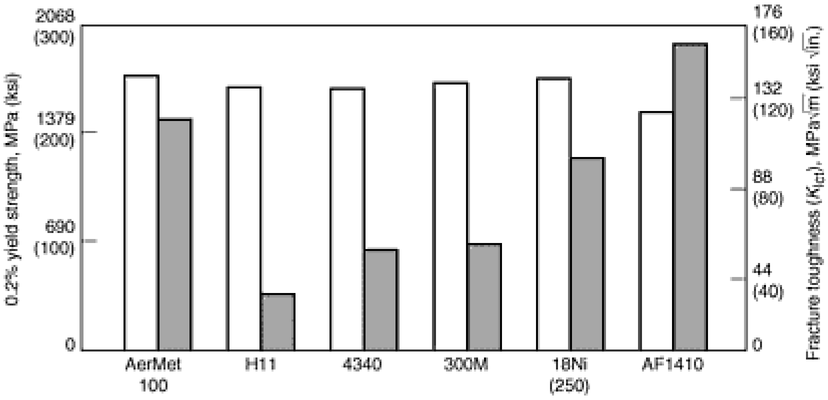


Fig. 3 Yield strength and fracture toughness (shaded bars) data for ultrahigh-strength steel

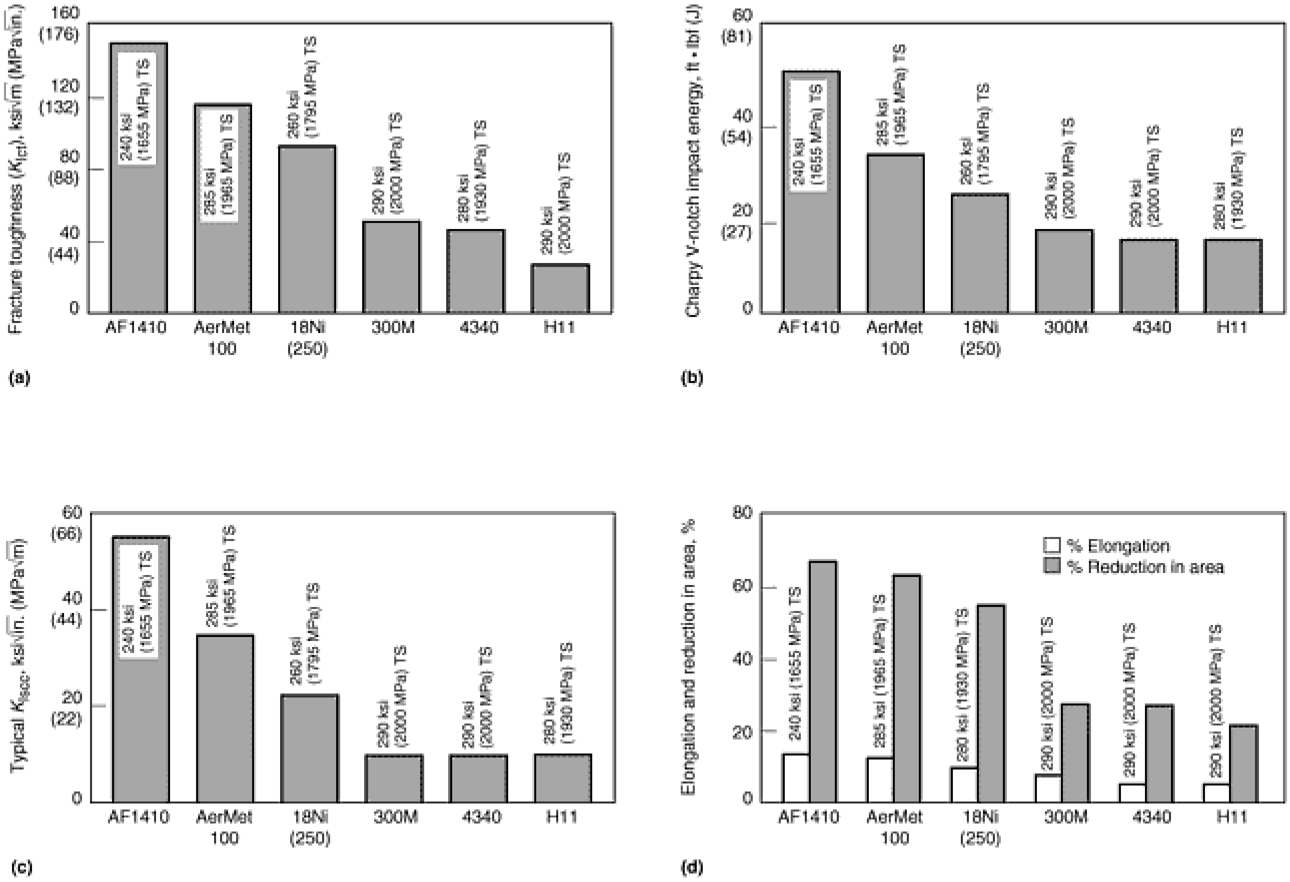


Fig. 4 Comparison of properties for ultrahigh-strength steels. (a) Fracture toughness data. (b) Charpy V-notch data. (c) Threshold stress intensity, K_{Iscc}, for stress-corrosion cracking data. (d) Ductility data

Wear-Resistant Austenitic Manganese Steels

Introduction

THE ORIGINAL AUSTENITIC MANGANESE STEEL, containing about 1.2% C and 12% Mn, was invented by Sir Robert Hadfield in 1882. Hadfield's steel was unique in that it combined high toughness and ductility with high work-hardening capacity and, usually, good resistance to wear. Consequently, it rapidly gained acceptance as a very useful engineering material.

Hadfield's austenitic manganese steel is still used extensively, with minor modifications in composition and heat treatment, primarily in the fields of earthmoving, mining, quarrying, oil well drilling, steelmaking, railroading, dredging, lumbering, cement manufacture, and clay production. Austenitic manganese steel is used in equipment for handling and processing earthen materials (such as rock crushers, grinding mills, dredge buckets, power shovel buckets and teeth, and pumps for handling gravel and rocks). Other applications include fragmentizer hammers and grates for automobile recycling and tank track pads for military applications. Another important use is in railway trackwork at frogs, switches, and crossings, where wheel impacts at intersections are especially severe. Because austenitic manganese steel resists metal-to-metal wear, it is used in sprockets, pinions, gears, wheels, conveyor chains, wear plates, and shoes.

Austenitic manganese steel has certain properties that tend to restrict its use. It is difficult to machine and usually has a yield strength of only 345 to 415 MPa (50 to 60 ksi). Consequently, it is not well suited for parts that require close-tolerance machining or that must resist plastic deformation when highly stressed in service. However, hammering, pressing, cold rolling, or explosion shocking of the surface raises the yield strength to provide a hard surface on a tough core structure.

Composition

Many variations of the original austenitic manganese steel have been proposed, often in unexploited patents, but only a few have been adopted as significant improvements. These usually involve variations of carbon and manganese, with or without additional alloys such as chromium, nickel, molybdenum, vanadium, titanium, and bismuth. The most common of these compositions, as listed in ASTM A 128, are given in Table 1.

Table 1 Standard composition ranges for austenitic manganese steel castings

ASTM A 128 grade	Composition, %						
	C	**Mn**	**Cr**	**Mo**	**Ni**	**Si (max)**	P (max)
A	1.05-1.35	11.0 min	. . .	. . .	. . .	1.00	**0.007**
B-1	0.9-1.05	11.5-14.0	. . .	. . .	. . .	1.00	**0.07**
B-2	1.05-1.2	11.5-14.0	. . .	. . .	. . .	1.00	**0.07**

B-3	1.12-1.28	11.5-14.0	. . .	. . .	. . .	1.00	**0.07**
B-4	1.2-1.35	11.5-14.0	. . .	. . .	. . .	1.00	**0.07**
C	1.05-1.35	11.5-14.0	1.5-2.5	. . .	. . .	1.00	**0.07**
D	0.07-1.3	11.5-14.0	. . .	. . .	3.0-4.0	1.00	**0.07**
E-1	0.7-1.3	11.5-14.0	. . .	0.9-1.2	. . .	1.00	**0.07**
E-2	1.05-1.45	11.5-14.0	. . .	1.8-2.1	. . .	1.00	**0.07**
F	**1.05-1.35**	**6.0-8.0**	**. . .**	**0.9-1.2**	**. . .**	**1.00**	**0.07**

The available assortment of wrought grades is smaller and usually approximates ASTM composition B-3. Some wrought grades contain about 0.8% C and either 3% Ni or 1% Mo. Large heat orders are usually required for. the production of wrought grades, while small lots more easily yield cast grades and their modifications. A manganese steel foundry may have several dozen modified grades on its production list. Modified grades are usually produced to meet the requirements of application, section size, casting size, cost, and weldability considerations. Higher manganese content steels (15 to 30% Mn) have also been developed for low magnetic permeability and cryogenic applications.

As-Cast Properties

Although austenitic manganese steels in the as-cast condition are generally considered too brittle for normal use, Table 2 demonstrates that there are exceptions to this rule. Mechanical properties are listed for five grades of as-cast austenitic manganese steels of various thicknesses. These data indicate that lowering carbon content to less than 1.1% and/or adding about 1.0% Mo or about 3.5% Ni results in commercially acceptable as-cast ductilities in light and moderate section thicknesses. These data also apply to weld deposits that are normally left in the as-deposited condition and therefore are essentially equivalent to material in the as-cast condition.

Table 2 Composition and mechanical properties of typical as-cast austenitic manganese steels

Composition, %				**Form**	**Section size**		**0.2% yield strength**		**Tensile strength**		**Elongation, %**	**Reduction in area, %**	**Charpy V-notch impact strength**		Hardness, HB
C	**Mn**	**Si**	**Other**		**mm**	**in.**	**MPa**	**ksi**	**MPa**	**ksi**			**J**	**ft·lbf**	
Plain manganese steels															
0.85	11.2	0.57	. . .	Round	25	1	. . .	. . .	440	64	14.5	. . .	. . .	. . .	**. . .**
0.95	13.0	0.51	. . .	Round	25	1	. . .	. . .	420	61	14	. . .	. . .	. . .	**. . .**

1.11	12.7	0.54	. . .	Round	25	1	360	52	450	65	4	. . .	. . .	. . .	**. . .**
1.27	11.7	0.56	. . .	Round	25	1	. . .	. . .	360	52	2	. . .	. . .	. . .	**. . .**
1.28	12.5	0.94	. . .	Keel block	102	4	. . .	. . .	330(a)	48(a)	1(a)	. . .	3.4	2.5	**245**
1.36	20.2	0.6	. . .	Y-block	51	2	. . .	. . .	425(a)	62(a)	1(a)	. . .	. . .	. . .	**283**
1% Mo manganese steels															
0.61	11.8	0.17	1.10 Mo	Round	25	1	315	46	710	103	27.5	23	. . .	. . .	**163**
0.75	13.9	0.58	0.90 Mo	Round	25	1	340	49	740	107	39.5	30	. . .	. . .	**183**
0.83	11.6	0.38	0.96 Mo	Round	25	1	345	50	695	101	30	29	. . .	. . .	**163**
0.89	14.1	0.54	1.00 Mo	Round	25	1	360	52	690	100	29.5	22	. . .	. . .	**196**
1.16	13.6	0.60	1.10 Mo	Round	25	1	400	58	560	81	13	15	. . .	. . .	**185**
0.93	13.6	0.67	0.96 Mo	Plate	25	1	365	53	510	74	11	16	72	53	**188**
0.99	12.6	0.6	0.87 Mo	Plate	25	1	. . .	. . .	460(a)	67(a)	6(a)	. . .	. . .	. . .	**. . .**
0.98	12.6	0.6	0.87 Mo	Plate	50	2	. . .	. . .	435(a)	63(a)	4(a)	. . .	. . .	. . .	**. . .**
0.95	12.6	0.6	0.87 Mo	Plate	102	4	345	50	385	56	4	4	. . .	. . .	**. . .**
1.30	13.1	0.78	0.99 Mo	Keel block	102	4	. . .	. . .	435(a)	63(a)	2(a)	. . .	8	6	**230**
1.33	19.8	0.6	0.99 Mo	Y-block	51	2	. . .	. . .	505(a)	73(a)	2.5(a)	. . .	. . .	. . .	**231**

2% Mo manganese steels															
0.52	14.3	1.47	2.4 Mo	Round	25	1	370	54	600	87	15.5	13	. . .	. . .	**220**
0.70	13.6	0.63	2.0 Mo	Round	25	1	360	52	785	114	41	29	. . .	. . .	**180**
0.75	14.1	0.99	2.0 Mo	Round	25	1	365	53	745	108	34.5	27	. . .	. . .	**183**
0.91	14.1	0.60	2.0 Mo	Round	25	1	395	57	705	102	27.5	21	. . .	. . .	**196**
1.24	14.1	0.64	3.0 Mo	Round	25	1	440	64	600	87	7.5	10	. . .	. . .	**235**
1.40	12.5	0.62	2.1 Mo	Round	25	1	420	61	550	80	3.5	5	. . .	. . .	**228**
1.34	12.0	0.43	2.2 Mo	Keel block	51	2	415	60	435	63	3.5	7	. . .	. . .	**235**
3.5% Ni manganese steels															
0.75	13.0	0.95	3.65 Ni	Round	25	1	295	43	655	95	36	26	. . .	. . .	**150**
0.80	13.5	0.53	3.61 Ni	Round	25	1	. . .	. . .	530	77	26	. . .	. . .	. . .	**. . .**
0.91	13.3	0.53	3.38 Ni	Round	25	1	. . .	. . .	510	74	24	. . .	. . .	. . .	**. . .**
6Mn-1Mo alloys															
0.90	5.8	0.37	1.46 Mo	Mill liner	102	4	325	47	340	49	2	. . .	9	7	**181**
1.00	6.0	0.43	1.03 Mo	Keel block	102	4	330	48	365	53	2	3	. . .	. . .	**195**
0.89	6.3	0.6	1.20 Mo	Plate	102	4	. . .	. . .	330[(a)]	48[(a)]	1[(a)]	. . .	. . .	. . .	**. . .**
1.27	**6.1**	**0.42**	**1.07**	**Keel**	**51**	**2**	**365**	**53**	**400**	**58**	**1**	**1**	**3**	**2**	**273**

			Mo	**block**											

(a) Properties converted from transverse bend tests on 6.4 × 13 mm ($\frac{1}{4} \times \frac{1}{2}$ in.) bars cut from castings and broken by center loading across 25 mm (1 in.) span

Commercial use of castings in the as-cast condition results in cost and energy savings and eliminates the problems of decarburization of thin castings during solution treatment and warpage during water quenching. Full ductility or toughness is not required in some applications of manganese steels.

Heavy Sections. As section thickness increases, the rate at which castings cool in sand molds decreases. This increases the opportunity for embrittlement by carbide precipitation. Shapes that tend to develop high residual stresses, such as cylinders and cones, can be particularly affected. These stresses most probably result from volume changes accompanying the carbide precipitation and austenite transformation that occur during the normal cooling of castings.

Figure 1 shows the volume changes that occur during the isothermal decomposition of a 1.25C-12.8Mn steel at temperatures between 850 and 500 °C (1560 and 930 °F), the principal range within which embrittlement occurs when a casting is cooled in its mold or reheated for reaustenitization. Between 850 and about 705 °C (1560 and 1300 °F), only carbides are precipitated, primarily as envelopes around austenite grains and as lamellar-type patches within grains. The lamellar carbide patches have the appearance of coarse pearlite, but they are actually carbide plates in austenite. Below 705 °C (1300 °F), and particularly between 650 and 550 °C (1200 and 1020 °F), pearlite nodules, nucleated by previously precipitated carbides, grow at a relatively rapid rate.

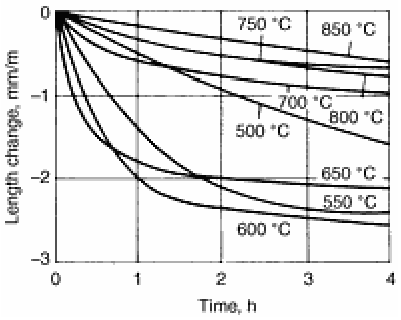


Fig. 1 Change in length of an austenitic 1.25C-12.8Mn steel during isothermal transformation

Transgranular acicular carbides also tend to precipitate below about 600 °C (1110 °F), especially in austenite containing more than about 1.1% C. This precipitation can continue down to about 300 °C (570 °F) in a 1.2C-12Mn steel. It may be followed by the transformation of some of the carbon-depleted austenite to martensite as the ambient temperature is approached.

Heat Treatment

Heat treatment strengthens austenitic manganese steel so that it can be used safely and reliably in a wide variety of engineering applications. Solution annealing and quenching, the standard treatment that produces normal tensile properties and the desired toughness, involves austenitizing followed quickly by water quenching. Variations of this treatment can be used to enhance specific desired properties such as yield strength and abrasion resistance.

The commercial heat treatment of manganese steel castings normally involves heating slowly to 1010 to 1090 °C (1850 to 2000 °F), soaking for 1 to 2 h per 25 mm (1 in.) of thickness at temperature, and then quenching in agitated water. There is some tendency for austenite grains to grow during soaking, especially in wrought manganese steels, although final austenite grain size in castings is largely determined by pouring temperature and solidification rate.

For grade E-2 manganese steel (see Table 1), a modified heat treatment is often specified or recommended. This treatment consists of heating castings to about 595 °C (1100 °F) and soaking them 8 to 12 h at temperature, which causes substantial amounts of pearlite to form in the structure. The castings are then further heated to about 980 °C (1800 °F) to reaustenitize the structure. This step converts the pearlitic areas to fine-grain austenite containing a dispersion of small carbide particles, which remain undissolved as long as the austenitizing temperature does not exceed about 1010 °C (1850 °F). Quenching then results in a dispersion-hardened austenite that is characterized by higher yield strength, higher hardness, and lower ductility than that obtained if the same steel were given a full solution treatment at a higher austenitizing temperature. This dispersion-hardening heat treatment permits a relatively high carbon content, which in turn can improve abrasion resistance.

Precautions. Speed of quenching is important, but it is difficult to increase beyond the rate of heat transfer from a hot surface to agitated water or beyond the rate fixed by the thermal conductivity of the metal. As a result, heavy-section castings have lower mechanical properties at the center than do thinner castings. Figure 2 shows the cooling rates that can be expected when metal plates of four different thicknesses are quenched in water. Table 3 lists average properties observed in castings of 1.11C-12.7Mn-0.5Si-0.043P steel water quenched from about 980 °C (1800 °F), which cooled the castings at the rates shown in Fig. 2.

Table 3 Average mechanical properties of 1.11C-12.7Mn-0.5Si-0.043P castings water quenched from 1040 °C (1900 °F)

Plate thickness		**Type of grain**	**Yield strength**		**Tensile strength**		**Elongation(a), %**	**Reduction in area, %**	Izod V-notch impact strength	
mm	**in.**		**MPa**	**ksi**	**MPa**	**ksi**			**J**	ft·lbf
50	2	Coarse	338	49	635	92	37.0	35.7	137	**101**
		Fine	365	53	820	119	45.5	37.4	134	**99**
83	$3\frac{1}{4}$	Coarse	345	50	620	90	25.0	34.5	133	**98**
		Fine	359	52	765	111	36.0	33.0	115	**85**
140	$5\frac{1}{2}$	Coarse	338	49	545	79	22.5	25.6	115	**85**
		Fine	352	51	705	102	32.0	28.3	100	**74**
190	$7\frac{1}{2}$	Coarse	324	47	455	66	18.0	25.1	77	**57**
		Fine	**359**	**52**	**725**	**105**	**33.5**	**29.2**	**66**	**49**

(a) In 25 mm (1 in.)

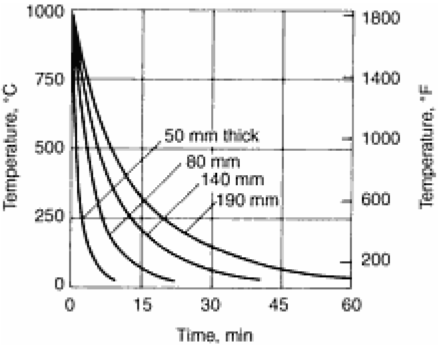


Fig. 2 Cooling curves for austenitic manganese steel of various thicknesses. Cooling curves are approximately equivalent to those for plate of the thicknesses indicated.

Residual stresses from quenching, coupled with the lower properties of heavy sections, establish the usual maximum thickness of commercial castings at about 127 to 152 mm (5 to 6 in.), although castings with sections up to 406 mm (16 in.) thick have been produced.

Mechanical Properties After Heat Treatment

As the section size of manganese steel increases, tensile strength and ductility decrease substantially in specimens cut from heat-treated castings. This occurs because, except under specialty controlled conditions, heavy sections do not solidify in the mold fast enough to prevent coarse grain size, a condition that is not altered by heat treatment. As shown in Table 3, fine-grain specimens may exhibit tensile strength and elongation as much as 30% greater than those of coarse-grain specimens.

Grain size also is the chief reason for the differences between cast and wrought manganese steels (the latter are usually of fine grain size). For cast grade B-2, the standard deviations for tensile strength and elongation are about 69 MPa (10 ksi) and 9%, respectively. The midrange values of 825 MPa (120 ksi) and 40% apply to sound, medium-grain cast specimens that have been properly heat treated. The scatter bands for this grade extend from 620 to 1035 MPa (90 to 150 ksi) for tensile strength and from 13 to 67% for elongation.

Mechanical properties vary with section size. Tensile strength, tensile elongation, reduction in area, and impact strength are substantially lower in 102 mm (4 in.) thick sections than in 25 mm (1 in.) thick sections. Because section thicknesses of production castings are often from 102 to 152 mm (4 to 6 in.), this factor is an important consideration for proper grade specification.

Notched-bar impact test values can be exceptionally high. Charpy test specimens are sometimes bent and dragged through the machine rather than being fractured. Occasionally, observed values are biased because of the incorrect preparation of specimens. Notches should be cut by precision grinding to minimize work hardening at the apex of the notch.

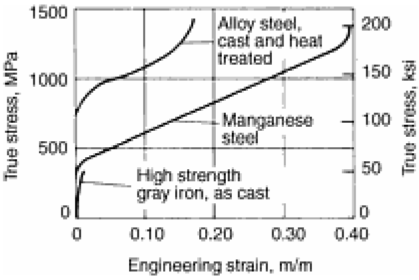
Austenitic manganese steel remains tough at subzero temperatures above the M_s, temperature. The steel is apparently immune to hydrogen embrittlement, although embrittlement has been produced in steels with low carbon content (<∼ 0.02%) and high manganese content. There is a gradual decrease in impact strength with decreasing temperature. The transition temperature is not well defined because there is no sharp inflection in the impact strength-temperature curve down to temperatures as low as -85 °C (-120 °F). At a given temperature and section size, nickel and manganese additions usually are beneficial for enhancing impact strength, while higher carbon and chromium levels are not.

Resistance to crack propagation is high and associated with very sluggish progressive failures. Because of this, any fatigue cracks that develop might be detected, and the affected part or parts removed from service before complete failure occurs, a capability that is a distinct advantage in railway track work. The fatigue limit of austenitic manganese steel has been reported as 270 MPa (39 ksi).

Yield strength and hardness vary only slightly with section size. The hardness of most grades is about 200 HB after solution annealing and quenching, but this value has little significance for estimating machinability or wear resistance.

Hardness increases so rapidly because of work hardening during machining or while in service that austenitic manganese steels must be evaluated on some basis other than hardness.

The true tensile characteristics of manganese steel are better revealed by the stress-strain curves in Fig. 3, which compare manganese steel with gray iron and with a heat-treated high-strength low-alloy steel of about the same nominal tensile strength. The low yield strength is significant and may prevent the selection of this alloy where slight or moderate deformation is undesirable, unless the usefulness of the parts in question can be restored by grinding. However, if deformation is immaterial, the low yield values may be considered temporary, that is, deformation will produce a new, higher yield strength corresponding to the amount of strain that is absorbed locally.



Alloy	Composition, %				
	C	**Mn**	**Si**	**Cr**	Other
Alloy steel, Q and T	0.29	1.30	0.52	0.37	**0.36 Mo**
Manganese steel	1.22	13.08	0.33	0.09	**0.05 Al**

(a) Q and T, quenched and tempered

Fig. 3 True stress versus engineering strain for manganese steel, cast alloy steel (quenched and tempered) of similar tensile strength, and a high-strength gray iron

Work Hardening

Manganese steels are unequaled in their ability to work harden, exceeding even the metastable austenitic stainless steels in this feature. For example, a standard grade of manganese steel containing 1.0 to 1.4% C and 10 to 14% Mn can work harden from an initial level of 220 HV to a maximum of more than 900 HV. After extended service, the hardness at the wearing surfaces of railway frogs typically ranges from 495 to 535 HB. Maximum attainable hardness depends on many factors, including specified composition, service limitations, method of work hardening, and preservice hardening procedures. It appears that rubbing under heavy pressure can produce higher values of maximum attainable hardness than those produced by simple impact.

Work-Hardening Methods. Work hardening is usually induced by impact, as from hammer blows. Light blows, even if they are of high velocity, cause shallow deformation with only superficial hardening even though the resulting surface hardness is ordinarily high. Heavy impact produces deeper hardening, usually with lower values of surface hardness. The course of flow under impact and the associated increase in hardness are shown in Fig. 4, which compares a standard 12% Mn steel with an air-hardening chromium-nickel-molybdenum alloy steel. Less well known is the fact that abrasion itself can produce work hardening.

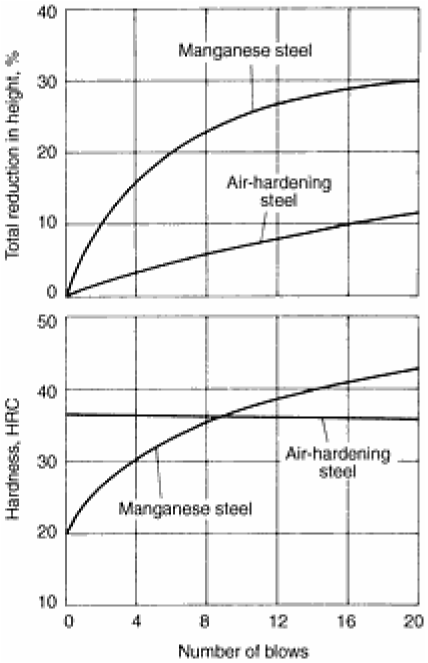


Fig. 4 Plastic flow (top) and work hardening (bottom) of a manganese steel and an air-hardening steel under repeat impact. Specimens 25 mm (1 in.) in both diameter and length were struck repeatedly on one end by blows with an impact energy of 680 J (500 ft·lbf). Composition and heat treatment of the manganese steels were 1.17C-12.8Mn-0.46Si, water quenched from 1010 °C (1850 °F). Composition and heat treatment of the air-hardening steel were: 0.74C-0.88Mn-0.30Si-0.75Ni-1.40Cr-0.38Mo; air cooled from 900 °C (1650 °F), reheated to 705 °C (1300 °F), and air cooled

Explosion hardening was developed as a substitute for hammer or press hardening to achieve hardening with less deformation. Pentaerythritol tetranitrate in the form of plastic explosive sheet 2.11 mm (0.083 in.) thick or mixtures of ammonium nitrate and trinitrotoluene (TNT) are cemented to the surface of the steel and detonated. Usually, three explosions are required to attain the desired hardness in railway track work.

Reheating

Before manganese steel parts are reheated in the field, the effects of such reheating must be seriously considered. Unlike ordinary structural steels, which become softer and more ductile when reheated, manganese steels suffer reduced ductility when reheated enough to induce carbide precipitation or transformation of the austenite. As a general rule, manganese steels should never be heated above 260 °C (500 °F) either intentionally or accidentally, unless such heating can be followed by standard solution annealing and quenching.

Wear Resistance

Compared to most other abrasion-resistant ferrous alloys, manganese steels are superior in toughness and moderate in cost, and it is primarily for these reasons that they are selected for a wide variety of abrasive applications. They are usually less resistant to abrasion than are martensitic white irons or martensitic high-carbon steels, but are often more resistant than pearlitic white irons or pearlitic steels.

The type of wear that is sustained has a major influence on the performance of manganese steels. They have excellent resistance to metal-to-metal wear, as in sheave wheels, crane wheels, and car wheels; good resistance to gouging abrasion, as in equipment for handling or crushing rock; intermediate resistance to high-stress (grinding) abrasion, as in ball-mill and rod-mill liners; and relatively low resistance to low-stress abrasion, as in equipment for handling loose sand or sand slurries.

Metal-to-Metal Contact. In applications involving metal-to-metal contact, the work hardening of manganese steel is a distinct advantage because it decreases the coefficient of friction and confers resistance to galling if temperatures are not excessive. Compressive loads, rather than impact loads, provide the deformation required, producing a smooth, hard surface that has good resistance to wear but does not abrade the contacting part. Sheaves, wear plates, and castings for railway track work are common applications of this type. Manganese steel also has been used in some water-lubricated bearings.

Abrasion. In applications that involve heavy blows or high compressive and structural stresses, the very hard and abrasion-resistant martensitic cast irons may wear more slowly than manganese steel. However, these irons usually fail by early fracture with a considerable portion of the original cross section unworn, whereas manganese steel may become almost paper thin before fracturing.

Pearlitic white cast iron, which has a hardness of about 400 to 450 HB, is equally brittle but less resistant to wear. Comparative tests on log washer lugs indicated that manganese steel was about 25% worn out with no breakage, whereas in the same period white iron lugs wore to the point of uselessness with 14% breakage. In clay crusher rolls, manganese steel lasted two to three times as long as white or chilled iron. In grinding barrel liners, cast irons lasted two to three years compared to ten years for manganese steel. Part of the superiority of manganese steel over white cast iron is attributed to greater freedom from breakage and spalling, but some is probably due to better intrinsic wear resistance.

Manganese steel chain, with endless links cast in interlocking molds, also provides resistance to wear, lasting three to nine times as long as heat-treated steel chain in certain applications. Manganese steel is valuable in conveyors as well as in dragline chain subjected to abrasion and used for carrying heavy loads.

Manganese steel is not satisfactorily resistant to wear by a stream of airborne abrasive particles (impingement erosion), such as in sandblasting or gritblasting equipment, and consequently should not be selected for such service.

The abrasion resistance of austenitic 12 to 14% Mn steels with various carbon contents has been compared with the resistance of other steels and white irons in a jaw crusher abrasion test (see Fig. 5). The wear rate for a quenched and tempered low-carbon low-alloy steel (ASTM 517, type B, at 269 HB), which was used as a comparative standard in each test, is also shown. When the relative wear rate (wear ratio) of each test material is plotted against increasing carbon content on a log-log scale, results for austenitic steels and irons tend to fall on a descending straight line, and results for martensitic steels and irons fall on a parallel line below the line for the austenitic alloys. A decrease in wear ratio represents a proportionate increase in abrasion resistance. Thus, Fig. 5 strongly supports the conclusion that the abrasion resistance of both austenitic and martensitic steels improves with increasing carbon content, and that, for a given carbon content, martensitic steels have better abrasion resistance than do austenitic steels. However, martensitic steels and white irons have limited resistance to gouging abrasion because of their lack of toughness. The wear ratios of pearlitic steels, steels, if plotted on Fig. 5, would lie above those of the austenitic steels. There is considerable scatter in the rates for pearlitic steels due to their wide variation in hardness for any given carbon content

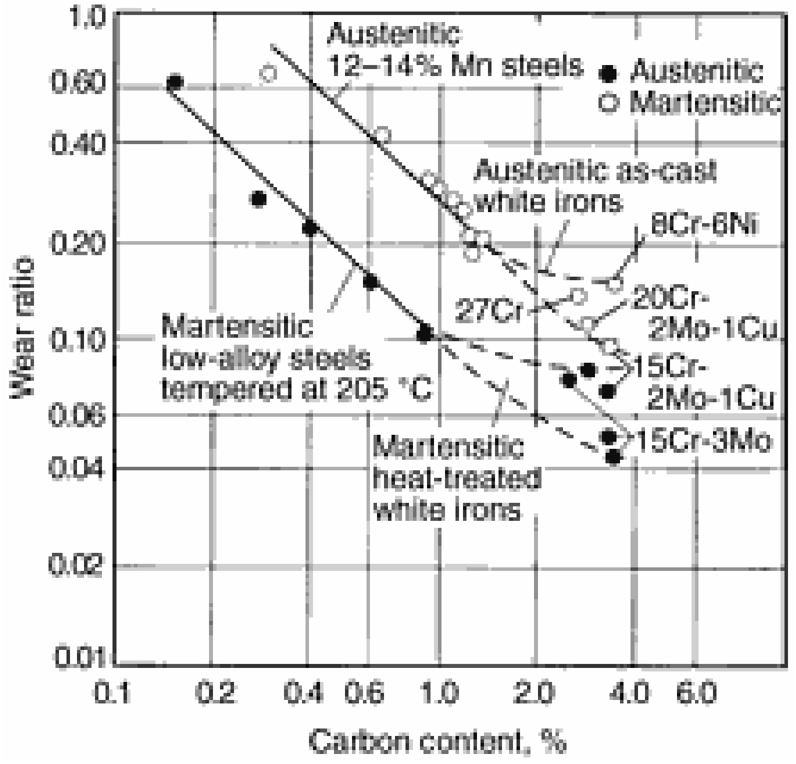


Fig. 5 Relative wear ratios of ferrous alloys in jaw crusher tests

Corrosion

Manganese steel is not corrosion resistant; it rusts readily. Furthermore, where corrosion and abrasion are combined, as they frequently are in mining and manufacturing environments, the metal may deteriorate or be dissolved at a rate only slightly lower than that of carbon steel. If the toughness or nonmagnetic nature of manganese steel is essential for a marine application, protection by galvanizing is usually satisfactory.

Hardenability of Carbon and Alloy Steels

Introduction

HARDENABILITY OF STEEL is the property that determines the depth and distribution of hardness induced by quenching. Steels that exhibit deep hardness penetration are considered to have high hardenability, while those that exhibit shallow hardness penetration are of low hardenability. Because the primary objective in quenching is to obtain satisfactory hardening to some desired depth, it follows that hardenability is usually the most important single factor in the selection of steel for heat treated parts.

Hardenability should not be confused with hardness as such or with maximum hardness. The maximum attainable hardness of any steel depends solely on carbon content. Also, the maximum hardness values that can be obtained with small test specimens under the fastest cooling rates of water quenching are nearly always higher than those developed under production heat treating conditions, because hardenability limitations in quenching larger sizes may result in less than 100% martensite formation. Effects of carbon and martensite content on hardness are shown in Fig. 1.

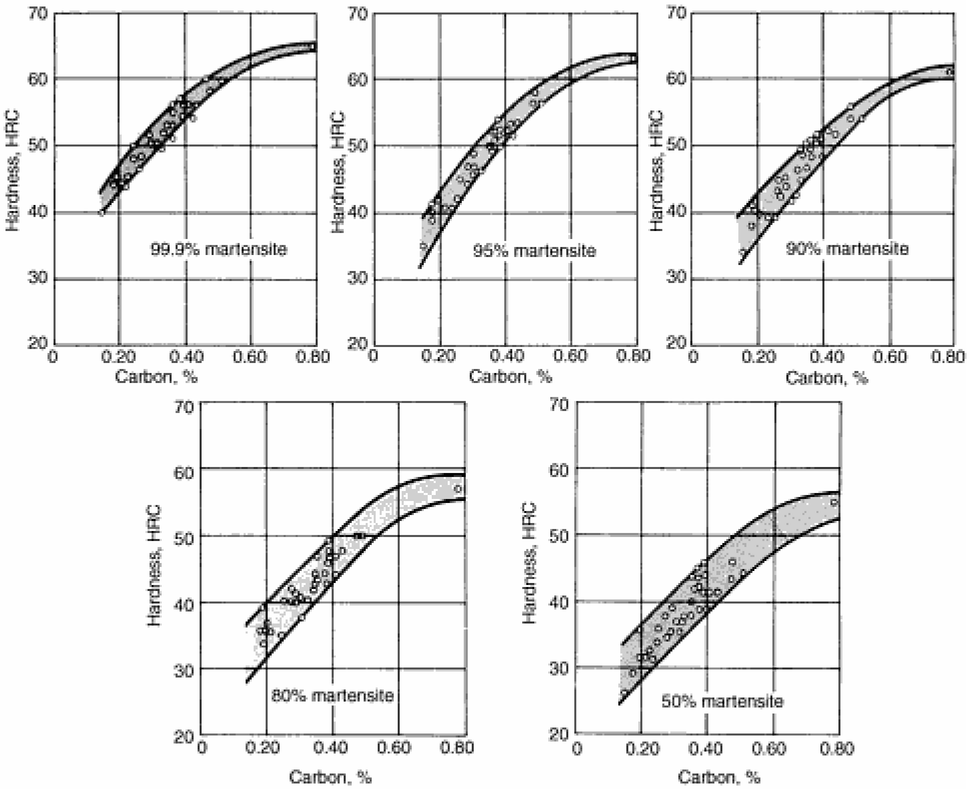


Fig. 1 Effect of carbon on hardness of martensite structures

The hardenability of steel is governed almost entirely by the chemical composition (carbon and alloy content) at the austenitizing temperature and the austenite grain size at the moment of quenching. In some instances, the chemical composition of the austenite may not be the same as that determined by chemical analysis, because some carbide may be undissolved at the austenitizing temperature. Such carbides would be reflected in the chemical analysis, but, being undissolved in the austenite, neither their carbon nor alloy content can contribute to hardenability. Also, by nucleating transformation products, undissolved carbides can actively decrease hardenability, This is especially important in high-carbon (0.50 to 1.10%) and alloy carburizing steels, which may contain excess carbides at the austenitizing temperature. Consequently, such factors as austenitizing temperature, time at temperature, and prior microstructure are sometimes very important variables when determining the basic hardenability of a specific steel composition.

Hardenability Testing

Hardenability of a steel is best assessed by studying the hardening response of the steel to cooling in a standardized configuration in which a variety of cooling rates can be easily and consistently reproduced from one test to another.

The end-quench, or Jominy, test fulfills the cooling rate requirements of hardenability testing most conveniently. The test specimen, a 1 in. (25.4 mm) diam bar 4 in. (102 mm) in length, is water quenched on one end face. The bar from which the specimen is made must be normalized before the test specimen is machined. The test involves heating the test specimen to the proper austenitizing temperature and then transferring it to a quenching fixture designed so that the specimen is held vertically 12.7 mm ($\frac{1}{2}$ in.) above an opening through which a column of water may be directed against the bottom face of the specimen. While the bottom end is being quenched by the column of water, the opposite end is cooling slowly in air, and intermediate positions along the specimen are cooling at intermediate rates, After the specimen has been quenched, parallel flats 180° apart are ground 0.015 in. (0.38 mm) deep on the cylindrical surface, Rockwell C hardness is measured at intervals of $\frac{1}{16}$ in. (1.59 mm) for alloy steels and $\frac{1}{32}$ in. (0.79 mm) for carbon steels, starting from the water-quenched end. A plot of these hardness values and their positions on the test bar, as shown in Fig. 2, indicates the relation between hardness and cooling rate, which, in effect, is the hardenability of the steel. Figure 2 also shows the cooling rate for the designated test positions. Details of the standard test method are contained in ASTM A 255 and SAE J406.

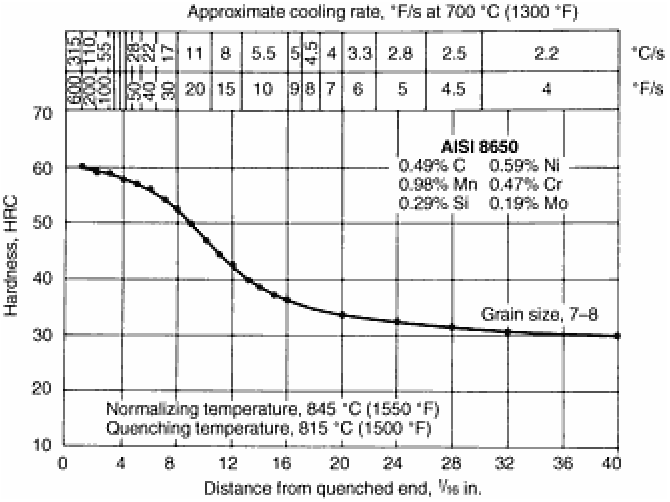


Fig. 2 Method for presenting end-quench hardenabililty data

The measured hardenability, curve shown in Fig. 2 for one specimen of 8650 steel falls about midway between the minimum and maximum hardenability curves that would be obtained from many heats of 8650 steel, and that define the limits of the so-called H-band for the 8650 steel. (Each grade of steel purchased to hardenability limits is represented by such an H-band that defines these limits.

The Carburized Hardenability Test. It is often necessary to determine the hardenability of the high-carbon case regions of carburized steels. Such information is important in controlling carburizing and quenching practice and in determining the ability of a specific steel to meet the hardness and case depth requirements of the carburized component manufactured from the steel.

Measurements of case hardenability are performed as follows. A standard end-quench bar is pack carburized for 8 h at 925 °C (1700 °F) and end quenched in the usual mariner. A comparison bar is simultaneously carburized in the same pack to determine carbon penetration. Successive layers are removed from it and analyzed chemically to determine the carbon content at various depths. When a carbon-penetration curve is established, depths to various carbon levels can be determined in the Jominy bar, assuming that distribution of carbon in the end-quench specimen is the same as in the carbon gradient bar. Longitudinal flats are then carefully ground to various depths on the end-quench bar (usually to carbon concentrations of 1.1, 1.0, 0.9, 0.8, and in some instances to as low as 0.6%), and hardenability is determined at these carbon levels by hardness traverses. In grinding, care must be exercised to avoid overheating and tempering, and in conducting hardness surveys, similar concern must be shown to ensure relating hardness to a single carbon level by remaining in the exact center of the flat. Rockwell A hardness readings are preferable to Rockwell C readings because they minimize the depth of indenter penetration into softer subsurface layers. Rockwell A values are converted to Rockwell C values for plotting, as shown in Fig. 3, which shows the curves of carburized hardenability of an EX 19 steel.

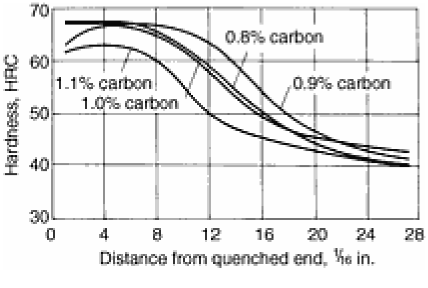
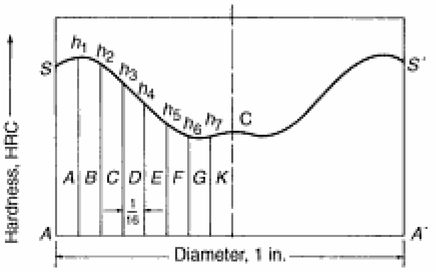


Fig. 3 Carburized hardenability, EX19 steel. Composition: 0.18 to 0.23 C, 0.90 to 1.20 Mn, 0.40 to 0.60 Cr, 0.08 to 0.15 Mo, 0.0005 min B

SAC Hardenability Test. This test is applicable to all plain carbon and low-alloy steels other than carbon tool steels and is suitable only for shallow-hardening steels that will not through harden in sizes larger than 25 mm (1 in.) in diameter. The surface-area-center (SAC) test is sometimes found to be more discriminating than the end-quench test for determining hardenability of shallow-hardening steels because of the sharp gradient on the end-quench curve.

The SAC test surveys hardnesses on an austenitized and quenched cross section. The specimen is 140 mm ($5\frac{1}{2}$ in.) long by 25.4 mm. (1 in.) in diameter. After normalizing at the specified temperature for 1 h and cooling in air, it is austenitized by holding at temperature for 30 min and quenching in water at 24 ± 5.5 °C (75 ± 10 °F), where it is allowed to remain until the temperature is uniform throughout the specimen.

After quenching, a cylinder 25.4 mm (1 in.) in length is cut from the middle of the hardened specimen. The cut faces of the cylinder are carefully ground parallel to remove any burning or tempering that might result from cutting and to assure that a flat fare will be presented to the anvil or fixture of the hardness-testing machine. Rockwell C hardness is measured on the cylindrical surface of the specimen at a minimum of four points at 90° angles to each other. The average of these reading becomes the surface reading. Next, a series of Rockwell C readings is taken on the cross section in steps of 1.59 mm ($\frac{1}{16}$ in.) from the surface to center. From these, a quantitative value can be computed and designated by a code known as the SAC number. The code consists of a set of three two-digit numbers, e.g., SAC No. 63-52-42. This indicates a surface hardness of 63 HRC, a Rockwell-inch area of 52, and a center hardness, of 42 HRC. The computation of area is shown in Fig. 4.



S = average surface hardness
h_1, h_2, h_3, etc. = average hardness at depths indicated
C = average center hardness

Then area of $A = \frac{S + h_1}{2} \times \frac{1}{16}$

Area of $B = \frac{h_1 + h_2}{2} \times \frac{1}{16}$

Total area $= 2(A + B + C + D + E + F + G + K)$
$= \frac{1}{8}(\frac{S}{2} + h_1 + h_2 + h_3 + h_4 + h_5 + h_6 + h_7 + \frac{C}{2})$

Fig. 4 SAC estimation of area

Effect of Carbon Content

Carbon has a dual effect in hardenable alloy steels. It controls maximum attainable hardness and contributes substantially to hardenability. The latter effect is substantially enhanced by the quantity and type of alloying elements present, because hardenability is the product of the carbon factor and the total of the alloy multiplying factors. It might be concluded, therefore, that increasing carbon content is the least expensive approach to improving hardenability. This is true to a degree, but several factors rule against the use of large amounts of carbon:

- High carbon content generally decreases toughness at room and subzero temperatures.
- It produces harder and more abrasive microstructures in the annealed conditions, which makes cold shearing, sawing, machining, and other forms of cold processing more difficult.
- It makes the steel more susceptible to hot shortness in hot working.
- It makes the steel more prone to cracking and distortion in heat treatment. Because of these disadvantages, more than 0.60% carbon is seldom used in steels for machine parts, except for springs and bearings, and steels with 0.50 to 0.60% carbon are used less frequently than those containing less

than 0.5%.

Figure 5 shows the differences between minimum hardenability curves for six series of steels. In each series, alloy content is essentially constant, and the effect of carbon content on hardenability can be observed over a range from 0.15 to 0.60%. The hardness effect is shown by the vertical distance between the curves at any position on the end-quench specimen--that is, for any cooling rate. This effect varies significantly, depending on the kind and amount of alloying elements. For instance, referring to Fig. 5(d), 5(e), and 5(f), an increase in carbon content from 0.35 to 0.50% in each of the three series of steels causes hardness increases (in Rockwell C points) at four different end-quench positions as follows:

Series	Distance from quenched surface, in.			
	$\frac{1}{16}$	$\frac{4}{16}$	$\frac{8}{16}$	$\frac{12}{16}$
41*xx*H	8	10	17	**20**
51*xx*H	8	13	9	**8**
86*xx*H	**8**	**12**	**18**	**12**

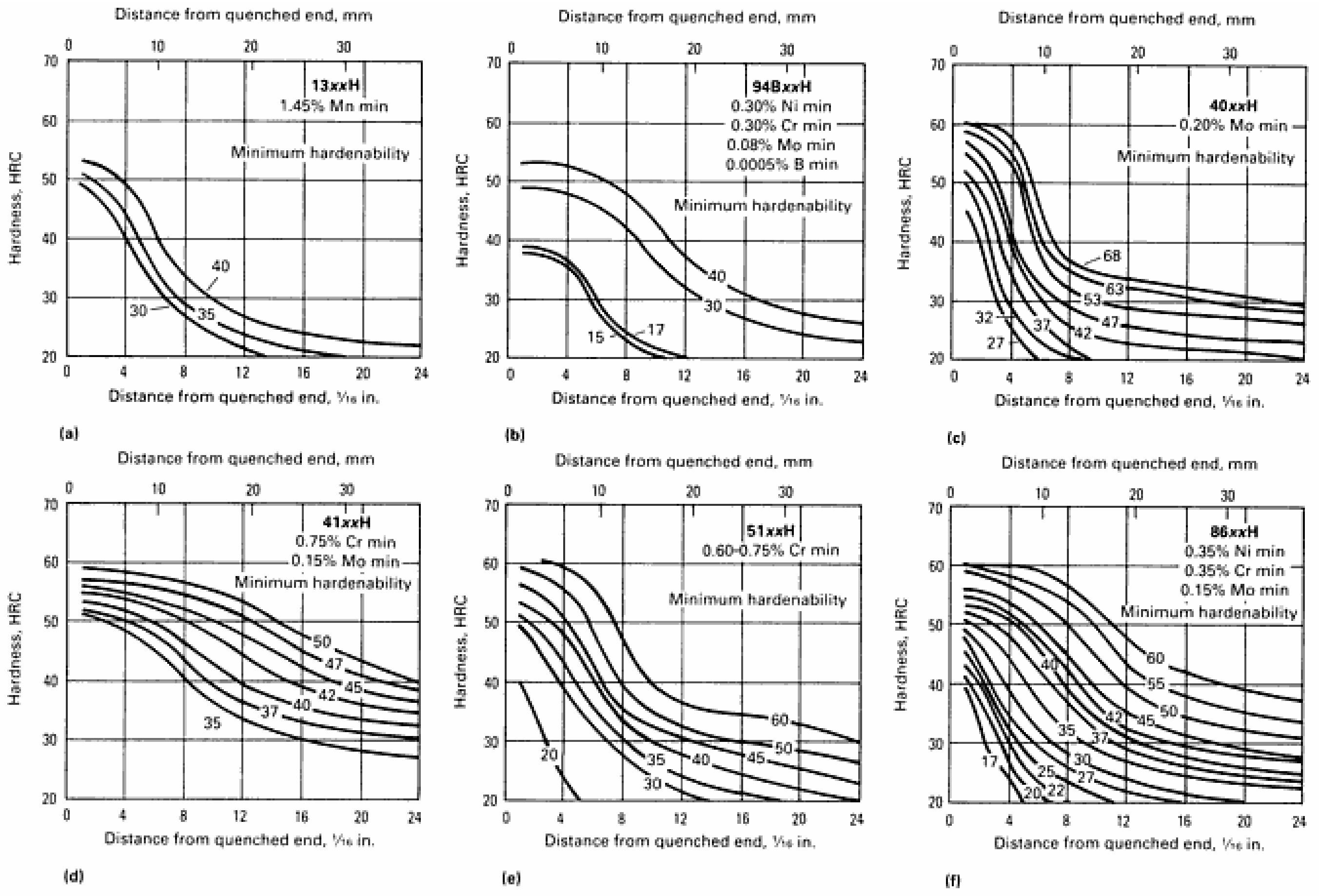


Fig. 5 Effect of carbon content on the minimum end-quench hardenability of six series of alloy H-steels. The number adjacent to each curve indicates the carbon content of the steel, to be inserted in place of *xx* in alloy designation.

The hardenability effect of carbon content is read on the horizontal axis. For example, in comparing the effect of carbon content on hardenability in 8650 versus 8630 at 45 HRC, the effect can be expressed as $\frac{6}{16}$ ($\frac{10}{16}$ minus $\frac{4}{16}$).

Similarly, at 45 HRC and with nominal carbon contents of 0.35 and 0.50%, the hardenability effect of carbon content is found to be much less in 51*xx* series steels and much greater in 41*xx* steels.

Considering the hardenability effect in terms of quenching speed, the cooling rate (or quenching speed) required to produce 45 HRC is affected more by 0.15% carbon with certain combinations of alloying elements than it is by other combinations. For instance, in a steel containing 0.75 Cr and 0.15 Mo (a 41*xx*H series steel, for example), increasing the carbon content by 0.15% lowers the required or critical cooling rate to obtain 45 HRC from 25 to 4.6 °C (45 to 8.3 °F) per second, while in a steel containing 0.75% Cr and no molybdenum (51*xx*H series), the same increase in carbon content lowers the cooling rate from 47 to 26 °C (85 to 37 °F) per second.

The practical significance of the effect of carbon and alloy contents on cooling rate is considerable. In a 51 mm (2 in.) diameter bar of 4150 steel, a hardness of 45 HRC can be obtained at half-radius using an oil quench without agitation. In a 4135 steel bar of the same diameter, to obtain the same hardness at half-radius would require a strongly agitated water quench. Comparing 32 mm (1$\frac{1}{4}$ in.) diameter bars of 5135 and 5150 steel, an agitated water quench will produce a hardness of 45 HRC at half-radius in the 5135 bar; the identical condition can be obtained in the 5150 bar using an oil quench with moderate agitation. To summarize, an increase or decrease in carbon content or an alloying addition, such as 0.15% molybdenum, affects the results obtained both in terms of the quenching severity required and the section size in which the desired results can be obtained.

The above method of rating differs from rating in terms of ideal critical diameter, which is based on hardening not to a given hardness but to 50% martensite at the center of a section, the hardness of which varies according to carbon content. Therefore, a part that must be hardened to a minimum hardness regardless of carbon content requires a steel rated in terms of that hardness and not in terms of 50% martensite, which varies in hardness. Figure 6 shows how steels are rated on the basis of ideal critical diameter by expressing the effect of carbon and alloy content on the section size that will harden to 50% martensite at the center, assuming an ideal quench. An ideal quench is defined as one that removes heat from the surface of the steel as fast as it is delivered to the surface.

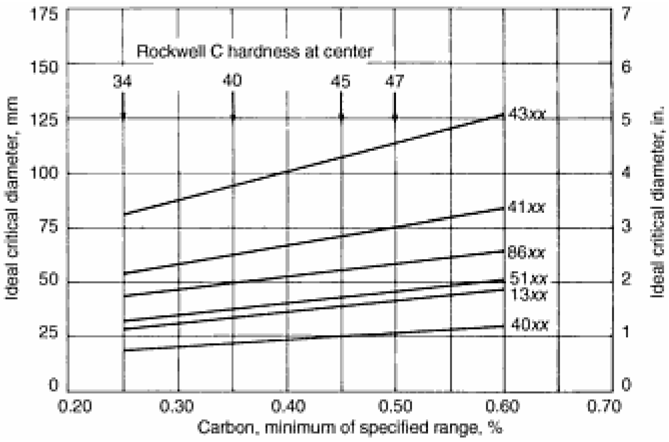


Fig. 6 Effect of carbon content on ideal critical diameter, calculated for the minimum chemical composition of each grade

Alloying Elements

The most important function of the alloying elements in heat treatable steel is to increase hardenability, which makes possible the hardening of larger sections and the use of an oil rather than a water quench to minimize distortion and avoid quench cracking.

When the standard alloy steels are considered, it is found that, for practical purposes, all compositions develop the same tensile properties when quenched to martensite and tempered to the same hardness below 50 HRC. However, it should not be inferred that all tempered martensites of the same hardness are alike in all respects. For instance, plain carbon martensites have lower reduction-in-area values than do alloy martensites. A further difference, sometimes important, is that fully quenched alloy steels require, for the same hardness levels, higher tempering temperatures than do carbon steels. This difference in tempering temperature may serve to reduce the residual stress level in finished parts. The stress reduction could be an advantage or a disadvantage, depending on whether a controlled compressive stress is desired in the part. Although tensile properties may not differ significantly from one alloy steel to another, considerable differences may exist in fracture toughness and low-temperature impact properties. In general, steels with a higher nickel content, such as 4320, 3310, and 4340, offer much greater toughness at a given hardness or hardenability level. In some applications, the toughness factor rather than hardenability may dictate steel selection, but hardenability is still important because steels that can be fully quenched to 100% martensite are much tougher than those that cannot.

Usually, the least expensive means of increasing hardenability at a given carbon content is by increasing the manganese content. Chromium and molybdenum, already referred to as increasing hardenability, are also among the most economical elements per unit of increased hardenability. Nickel is the most expensive per unit, but is warranted when toughness is a prime consideration.

Another potent and economical alloying element is boron, which markedly increased hardenability when added to a fully deoxidized steel. The effects of boron on hardenability are unique in several respects: (a) a very small amount of boron (about 0.001%) has a powerful effect on hardenability; (b) the effect of boron on hardenability is much less in high-carbon than in low-carbon steels; (c) nitrogen and deoxidizers influence the effectiveness of boron; (d) high-temperature treatment reduces the hardenability effect of boron. (Recommended austenitizing temperatures for boron H-steels are given with the H-bands.)

Effect of Grain Size

The hardenability of a carbon steel may increase as much as 50% with an increase in austenite grain size from ASTM 8 (6 to 10) to ASTM 3 (1 to 4). The effect becomes more pronounced if the carbon content is increased at the same time. When the danger of quench cracking is remote (no abrupt changes in section thickness) and engineering considerations permit, it can sometimes appear to be more practical to use coarser-grained steel than a fine-grained or more expensive alloy steel to obtain hardenability. However, this is not recommended, because the use of coarser-grained steels usually involves a serious sacrifice in notch toughness and may lead to other difficulties.

Variations Within Heats

Segregation or carbon, manganese, and other elements always occurs during ingot pouring and solidification. As a result, hardenability of the steel in these segregated portions will differ from that in the remainder of the ingot. In general, specimens taken from the top of the ingot have higher hardenability than steel from the middle, and specimens from the bottom of the ingot will have lower hardenability than steel from the middle.

The same effect is observed in alloy steels. End-quench hardenability test results for one heat of 4028 steel (Fig. 7) show higher hardenability for a cast bar taken from the top of the last ingot of the heat than for a specimen from the melting floor labeled "cast end-quench specimen." The latter was taken from about the middle of the heat.

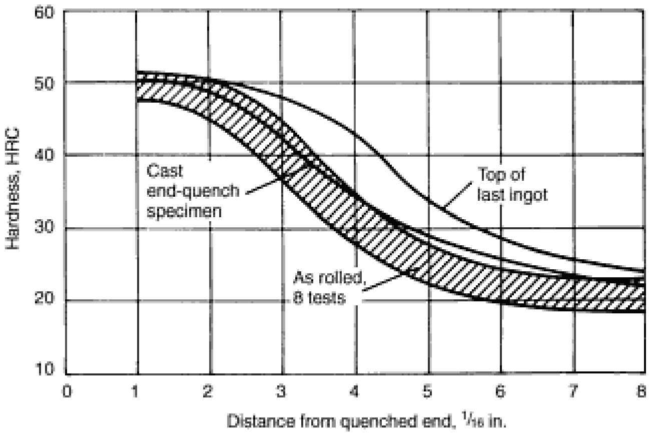


Fig. 7 Variation of hardenability within a heat of 4028 steel

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Determining Hardenability Requirements

The basic information needed before a steel with adequate hardenability can be specified includes: (a) the as-quenched hardness required prior to tempering to final hardness that will produce the best stress-resisting microstructure; (b) the depth below the surface to which this hardness must extend; and (c) the quenching medium that should used in hardening.

As-Quenched Hardness. A common and economical practice is to select the steel with the lowest carbon content that will produce the indicated as-quenched hardness using the quenching medium available (or one that can be made available). Following this procedure, the structures possessing the indicated hardnesses would be fully hardened. That is, they would contain more than 90% martensite, which is a common and practical definition of full hardening.

Depth of Hardening. The depth and percentage martensite to which parts are hardened can affect their serviceability, but it always affects the hardenability required and, therefore, the cost. In parts less highly stressed in bending, hardening to 80% martensite at three-quarter-radius of the part as finished may be sufficient; in other parts, even less depth may be required. The latter include principally those parts designed for low deflection under load, in which even the exterior regions are only moderately stressed. In contrast, some parts loaded principally in tension and others operating at high hardness levels, such as springs of all types, are usually hardened more nearly through the section. In automobile leaf springs, the leaves are designed with a low section modulus in the direction of loading. The allowable deflection is large, and most of the cross section is highly stressed.

In general, hardening need be no deeper than is required to provide the strength to sustain the load at any given depth below the surface. When these requirements are not wholly justified, the results are overspecification of steel at higher cost, and greater likelihood of distortion and quench cracking.

Quenching Media. The cooling potential of quenching media is a critical factor in heat treating processes because of its contribution to attaining the minimum hardenability requirement of the part or section being heat treated. The cooling potential, a measure of quenching severity, can be varied over a rather wide range by (a) selection of a particular quenching medium, (b) control of agitation, and (c) additives that improve the cooling capability of the quenchant.

In general, the more severe the quenchant and the less symmetrical the part being quenched, the greater are the size and shape changes that result from quenching and the greater is the risk of quench cracking. Consequently, although water quenching is less costly than oil quenching and water-quenching steels are less expensive than those requiring oil quenching, it is important that parts to be hardened be carefully reviewed to determine whether the amount of distortion and the possibility of cracking as a result of water quenching will permit taking advantage of the lower cost of water quenching. Oil, salt, and synthetic water-polymer quenchants are alternatives, but their use often requires steels of higher alloy content to satisfy hardenability requirements.

A rule regarding selection of a steel and quenching medium for a given part is that the steel should have a minimum hardenability not exceeding that required by the quenching severity of the medium selected. The steel should also contain the lowest carbon content compatible with required hardness and strength properties. This rule is based on the fact that the quench cracking susceptibility of steels increases with a decrease in M_s temperature, and/or an increase in carbon content.

Table 1 lists typical quenching severities, or "H" values, for the common quenching media and conditions. These data are for media containing no additives. Considerable improvement in the cooling capability can be obtained by such additions as polyalkylene glycol (polymer) to water, proprietary additives to oil, and water to hot salt.

Table 1 Quenching severities, H, for various media and quenching conditions

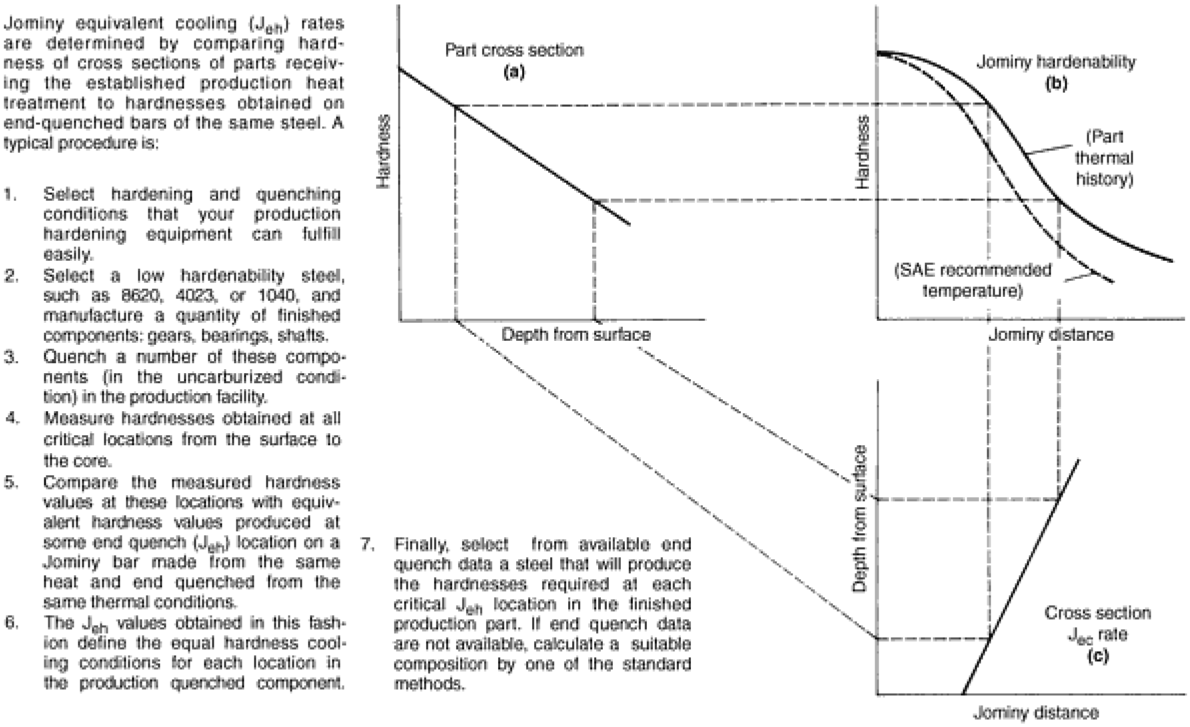
Quenchant agitation	**Typical flow rates**		Typical H values			
	m/min	**sfm**	**Air**	**Mineral oil**	**Water**	Brine
None	0	0	0.02	0.20-0.30	0.9-1.0	**2.0**
Mild	15	50	. . .	0.20-0.35	1.0-1.1	**2.1**
Moderate	30	100	. . .	0.35-0.40	1.2-1.3	**. . .**
Good	61	200	0.05	0.40-0.60	1.4-2.0	**. . .**

Hardenability versus Size and Shape. When end-quench data such as those shown in Fig. 2 are available, either of two methods can be used to estimate the hardenability that a steel part of given size and configuration must have in order for it to achieve desired hardness, strength, and microstructure at critical locations when benched in various production media. These methods comprise:

1. The correlation of end-quench hardness (J_{eh}) with equivalent hardness locations in variously quenched shapes
2. The correlation of end-quench cooling-rate data (J_{ec}) with equivalent cooling-rate locations in

variously quenched production shapes

Method 1, which is described in Fig. 8, is the more accurate and preferred method, because in practice it has been found that, when cooling at the same rates, large sections produce somewhat lower hardnesses than smaller sections.



Jominy equivalent cooling (J_{eh}) rates are determined by comparing hardness of cross sections of parts receiving the established production heat treatment to hardnesses obtained on end-quenched bars of the same steel. A typical procedure is:

1. Select hardening and quenching conditions that your production hardening equipment can fulfill easily.
2. Select a low hardenability steel, such as 8620, 4023, or 1040, and manufacture a quantity of finished components: gears, bearings, shafts.
3. Quench a number of these components (in the uncarburized condition) in the production facility.
4. Measure hardnesses obtained at all critical locations from the surface to the core.
5. Compare the measured hardness values at these locations with equivalent hardness values produced at some end quench (J_{eh}) location on a Jominy bar made from the same heat and end quenched from the same thermal conditions.
6. The J_{eh} values obtained in this fashion define the equal hardness cooling conditions for each location in the production quenched component.
7. Finally, select from available end quench data a steel that will produce the hardnesses required at each critical J_{eh} location in the finished production part. If end quench data are not available, calculate a suitable composition by one of the standard methods.

Fig. 8 Determination of Jominy equivalent cooling (J_{eh}) rates

Service Characteristics of Carbon and Alloy Steels

Wear Resistance of Steels

WEAR of metals occurs by the plastic displacement of surface and near-surface material and by the detachment of particles that form wear debris. In metals, this process may occur by contact with other metals, nonmetallic solids, flowing liquids, or solid particles or liquid droplets entrained in flowing gases.

Wear involves damage to a solid surface due to relative motion between that surface and one or more contacting substances and generally consists of a progressive loss of material from the wearing surface. It may include oxidation, corrosion, creep, fatigue, frictional effects, battering from impact, pseudomachining due to rough surfaces, and the cutting and deformation action of abrasive particles. This complex is difficult to handle rigorously; consequently, investigations are usually limited to only certain facets of wear. Mechanical effects are those usually considered, whereby local deformation or metal removal results from stresses applied either directly or indirectly to a surface.

Wear can result in alteration of critical dimensions, increased vibration, fatigue damage, clogging of critical passages and contacts by debris, generation of abrasive particles, leaking fluid from enclosures, inefficient operation, and system failure.

Classification of Wear

One of the simplest classifications of wear is based on the presence or absence of effective lubricants--namely, lubricated and nonlubricated wear. (The various types of lubrication are described later in this article.) Wear may also be classified by mechanisms. For example, the following wear mode classification was used in *Friction, Lubrication, and Wear Technology,* Volume 18 of *ASM Handbook:*

Wear by particles or fluids

- Abrasive wear
- Polishing wear
- Solid particle erosion
- Cavitation erosion
- Liquid impingement erosion
- Slurry erosion

Wear by rolling, sliding, or impact

- Sliding and adhesive wear
- Fretting wear
- Rolling contact wear
- Impact wear

Chemically assisted wear

- Corrosive wear
- Oxidational wear

Classifications based on wear mechanisms have generally emphasized one or more of the following factors: removal of individual atoms, plastic deformation, ductile or brittle fracture, and cutting, fatigue, adhesion, and chemical-electrochemical effects.

An inherent problem exists in any classification scheme that relies mainly on labels implying mechanisms. Overuse of such labels (that is, use without adequate experimental evidence) could lead to the misconception that knowledge of a particular wear situation is well understood. This, in turn, may discourage innovative efforts in wear control.

A third approach to wear classification emphasizes the nature of the contacting materials and the experimental conditions, using descriptive terms that are widely understood and accepted. The following is an example of this type of classification:

Metal against nonmetallic abrasive

- High-stress gouging or grinding:
    - Wet, as in ball and rod mills
    - Dry, as in jaw-type or roll-type ore crushers
- Low-stress scratching or sliding:
    - Wet, such as conveyor screws for wet sand
    - Dry, as against plows or earthmoving devices operating in dry soil

- Impact of loose abrasive (erosion):
    - Wet, as against impellers in slurry pumps
    - Dry, as in sandblasting

Metal against metal

- Sliding:
    - Lubricated, such as engine crosshead or shaft in a bearing
    - Nonlubricated, such as fasteners, nuts, and bolts
- Rolling:
    - Lubricated, such as roller bearings and gears
    - Nonlubricated, such as wheels on tracks

Liquid or vapor impingement on metals

- Wet steam, such as turbines
- Combustion gases, such as gas turbines
- Water, such as pump impellers
- Cavitations, as in turbulent, high-velocity flowing liquids

Frequently, these conditions are combined in service so an application that was originally metal against metal may evolve into metal against nonmetal wear, such as the generation of oxide wear debris and the introduction of nonmetallic particles through imperfect seals. Other combinations include rolling with sliding and lubricated-nonlubricated situations.

Wear Testing and Evaluation

It is often difficult to compare published wear data obtained by different investigators, either because some of the experimental conditions are not reported or because significantly different wear tests have been used. Wear testing has not yet been adequately standardized. Hundreds of different wear test devices and procedures have been described in the technical literature. Many of these are based on simple configurations, such as pin-on-disk, block-on-ring, ring-on-ring, or cylinder-on-cylinder. Many other devices have been designed to simulate as closely as possible actual operating conditions for actual components. This is frequently a desirable approach, particularly if the designer has difficulty adapting published wear data to his own situation, although it contributes to the proliferation of wear tests.

Despite the great variety of wear tests, the main variables in sliding mechanical wear may be identified by asking three simple questions:

- Is the system lubricated or unlubricated?
- Is most of the wear debris removed?
- Is the wearing surface in steady contact with another surface?

Types of wear tests are discussed in greater detail in the Section "Mechanical, Wear, and Corrosion Testing" in this Handbook.

Reporting wear data is not well standardized; however, some of the more common reporting methods are discussed below. The simplest and most widely used way to summarize wear data is to note changes in length, volume, or mass (or these same measures per unit time) for specified conditions. Wear resistance is sometimes given as the inverse of one of these quantities. Of course, when expressed in this manner, the results are not materials constants, because they are based on experimental conditions.

Several models of sliding wear lead to the prediction for volume change:

$$\Delta V = \mathrm{k}LS/3H$$

where L is load, S is sliding distance, H is Vickers hardness, and k is a coefficient. Therefore, wear rate is commonly reported as $\Delta V/L$. For mild wear, k would be approximately 10^{-8} to 10^{-7}; for severe wear, it would be about 10^{-4} to 10^{-3}. Sometimes a wear factor defined as $\Delta V/SL$ or $\mathrm{k}/3H$ is used.

Wear is sometimes reported as "specific wear," or d/PS, where d is depth of wear, P is bearing pressure, and S is sliding distance. Wear data may also be expressed as lifetime-in-service when wear is the main determinant of lifetime. Wear rates are commonly reported as values that are relative to the wear of a standard material subjected to the same conditions as the test specimen. The use of a good reference material is almost imperative. It is the only reasonable way of ranking materials for comparison to other wear situations, because values of metal loss generally do not agree even when different investigators make every effort to subject specimens to identical test conditions. In fact, the amount of metal loss from different specimens of a standard reference material tested under standard conditions in a single test apparatus can vary by as much as 25% over an extended period, with no apparent trend implying that test conditions are changing systematically.

Wear Rate Transitions. Wear testing of many materials results in a linear variation of wear with load. It is therefore tempting to extrapolate such data to higher load situations, especially because simple wear models generally predict a linear load dependence. However, this is not a reliable practice because one or more wear rate transitions associated with changes in microstructure, temperature, or other test conditions can occur.

Several examples of such transitions are summarized in Table 1 for the wear of gray iron pins in a series of pin-on-disk tests. At low loads, the wear debris was mainly oxide, but at higher loads, the debris particles were metal flakes approximately five times larger than the oxide debris particles. Lowest wear rates in both regimes were found for ASTM type A flake graphite of size 3 to 4, randomly distributed in a pearlite matrix. Similar transitions with load are observed for many ferrous materials.

Table 1 Wear of gray iron pins in pin-on-disk tests

Iron structure		**Free ferrite, %**	**Transition load, kg**	Weight loss[(a)], g		
Graphite form	**Graphite size**			**Running-in wear[(b)]**	**Wear in mild regions[(c)]**	Wear in severe regions[(c)]
ASTM type A	3-4	5	1.70	1.90	0.0	**5.0**
	4	10	2.10	2.90	0.016	**5.0**
ASTM type D, some type A	5-6	15	3.55	1.45	0.083	**13.2**

ASTM type E	**6-7**	**25**	**3.20**	**0.40**	**0.049**	**22.0**

(a) Per kilogram of load.

(b) At the end of 6700 m of sliding.

(c) At the end of 10,000 m of sliding

White-Etching Layers. In the wear literature, reference is frequently made to a "white layer" or "white-etching layer." This white layer is usually much harder than the adjacent material, but seldom are any other characteristics of the layer clearly defined. Some confusion arises because there are many distinct types of "white layer." For example, the white layer may be a region of martensite developed during frictional heating and rapid cooling. In other wear situations, it may be a nitride layer formed by special surface treatment or it may be a highly deformed region with a fine cell microstructure.

Wear debris consists of pieces of material (varied in size and shape) that become loose during wear. The structure and properties of the debris can provide clues to the type of wear involved and the prevailing conditions during its formation.

Wear debris is a sensitive indicator of wear mechanisms and operating conditions. When the debris from two different test devices is similar, comparable wear situations can be expected. This principle can be extended to comparisons of published wear data (when wear debris information is given) and even to actual operating equipment. In the latter case, wear debris analysis facilitates monitoring of wear conditions, thus providing advance warning of wear failure.

Abrasive Wear

Abrasive wear involves the plowing of localized surface contacts through a softer mating material. The wear is most frequently caused by nonmetallic materials, but metallic particles can also cause abrasion. Generally, a substance is seriously abraded or scratched only by materials that are harder than itself. Most protection against abrasion is based on this generalization, but there are exceptions.

When abrasion takes place under high surface loads, such as in ball or rod mills or in ore-crushing devices, the action is more complex. The abrasive is continually broken into smaller and smaller fragments. As a result, action that starts as gouging and surface deformation under the forces that drive large particles against the surface becomes transformed into cutting and scratching as the particles become finer and more angular.

Types of Abrasive Wear. Abrasive wear can take the form of gouging abrasion, high-stress grinding abrasion, or erosion and low-stress scratching abrasion:

- *Gouging abrasion* involves removal of relatively coarse particles from the steel wearing surface and is similar to the removal of metal by machining or grinding with a coarse-grit grinding wheel. In service, this occurs on parts such as dipper teeth handling large sharp rocks, impact pulverizer hammers, and some chute liners. Gouging abrasion is at least partially responsible for wear in crusher liners.
- *High-stress grinding abrasion* involves removal of relatively fine (microscopic) particles from the wearing surface. The pinching action of two metal surfaces causes the abrasive to fragment. Unit compressive or shear stresses are very high. Consequently, the harder abrasives, such as quartz, are capable of indenting or scratching steel with a hardness of 65 to 70 HRC. Metal may be removed from the wearing surface by microscopic gouging or by a combination of local plastic flow and microcracking. Ball milling is a good example of grinding abrasion. In machinery, such abrasion occurs where parts rub against each other in a gritty environment.
- *Erosion and low-stress scratching abrasion* occur by very light rubbing contact from sharp abrasive particles. The stresses are due mainly to velocity and are normally insufficient to cause much

fragmentation of the abrasive. Examples of this exist on screens, chute liners handling sand, parts handling sand slurries, and parts exposed to airborne abrasives. Erosion also can occur when a flowing liquid containing suspended abrasive particles flows over a surface. Liquids themselves can cause erosion when a stream of liquid impinges directly on a surface, when fluid flow conditions induce cavitation in the liquid adjacent to a surface, and when droplets carried by a flowing gas impact against a surface. Corrosion may be involved in the erosion process, especially in liquids or when the temperature is above room ambient.

Abrasion Testing. When abrasion testing of materials under actual service conditions is not practical, a laboratory abrasion test that closely simulates service conditions should be selected. However, in laboratory testing, the following factors must be considered:

- The position of the abrasive--whether fixed, as in abrasive paper (two-body abrasion), or free to rotate, as in loose sand (three-body abrasion)
- The size, shape, and hardness values of the dominant abrasive (usually the hardest component in a mixture)
- The direction and speed of relative motion during abrasion
- The contact pressures or loads in the system

To simulate low-stress or scratching abrasion with loose abrasive, a rubber wheel test has been found useful. Figure 1 shows test results for a wide range of materials. The least wear-resistant material in Fig. 1 wears 1500 times faster than the most wear-resistant material.

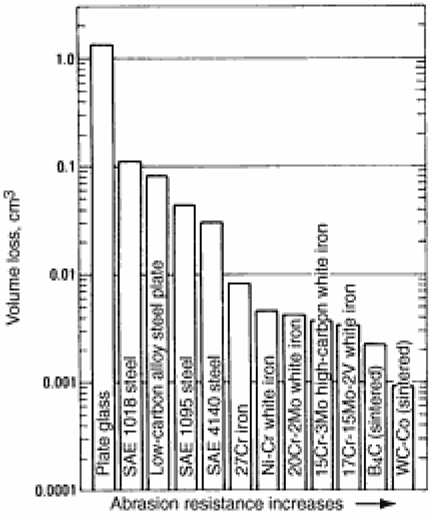
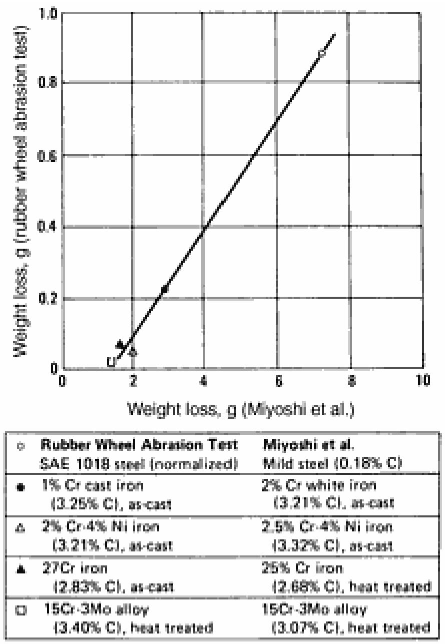


Fig. 1 Rubber wheel abrasion test results in terms of volume loss, normalized to 55 Durometer hardness of the rubber wheel. Note the logarithmic scale for wear loss.

Correlations between Dissimilar Abrasion Tests. In some applications, data from one type of abrasion test can be used to predict relative wear rates under quite different conditions. For instance, several steels and cast irons were tested in a rubber wheel device and also by movement through an abrasive slurry. Despite the obvious differences in test conditions, correlation between results from both types of tests is quite good (see Fig. 2). In both cases, the abrasive was loose and the stresses low. If test conditions were more dissimilar, the simple correlation could not be expected to continue.



	Rubber Wheel Abrasion Test	Miyoshi et al.
○	SAE 1018 steel (normalized)	Mild steel (0.18% C)
●	1% Cr cast iron (3.25% C), as-cast	2% Cr white iron (3.21% C), as-cast
△	2% Cr-4% Ni iron (3.21% C), as-cast	2.5% Cr-4% Ni iron (3.32% C), as-cast
▲	27Cr iron (2.83% C), as-cast	25% Cr iron (2.68% C), heat treated
□	15Cr-3Mo alloy (3.40% C), heat treated	15Cr-3Mo alloy (3.07% C), heat treated

Fig. 2 Correlation between results of the rubber wheel abrasion test and Sumitomo Metal Industries abrasion-testing machine

Abrasive Particle Size. Airborne dirt is a chronic cause of excessive ring wear in an internal combustion engine. Proper maintenance and design of filter equipment are essential controls, Prevention of air leaks between filters and the engine is also imperative. Lubricating oil contaminated with dirt is a less frequent problem, but design and maintenance of oil filters and seals are necessary considerations to control occurrence. When particles of dirt in an engine reach a certain size, wear subsides and the dirt particles often allay rather than increase friction. Test data in Fig. 3 for piston ring wear indicate that abrasion is most severe at a particle size of about 20 μm. Apparently, the lubricating effectiveness of the oil over a wide range of viscosities has little influence on the wear peak established by particle size.

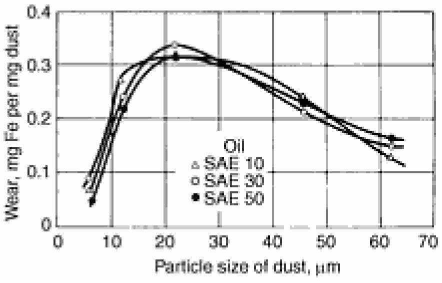


Fig. 3 Effect of dust particle size on the wear of engine piston rings lubricated by oils of three different viscosities

Hardness of the abrasive significantly influences abrasion. As the hardness of the abrasive increases, variations in wear rates for different steels diminish. Conversely, as the abrasive hardness decreases, differences in the hardness and microstructure of steels become more important.

Hardness of Metal. Wear problems are solved, wholly or in part, by the proper selection of metals (see Table 2). Metal hardness is one of the most important characteristics to consider when selecting for maximum wear. If other factors remain relatively constant, comparisons of hardness values provide an approximate guide to relative wear behavior among different metals, especially in metal-to-metal sliding and abrasive applications. However, hardness alone cannot be expected to determine the optimal material choice for a given application. Later sections of this article describe other factors to be considered when selecting material for wear resistance, one of the most important of which is microstructure.

Table 2 Relative hardness and abrasion resistance of several steels against hard and soft abrasives

Material	**Carbon, %**	**Hardness, HV**	**Wear resistance(a)**		**Flint abrasive(b)**			Glass abrasive(c)		
			SiC 180 grit	**Al_2O_3 180 grit**	**Relative hardness(d)**	**Wear resistance(a)**		**Relative hardness(d)**	Wear resistance(a)	
						180 grit	**36 grit**		**180-200 grit**	30 grit
1.6Ni-1.1Cr-0.26Mo steel, hardened and tempered	0.37	352	. . .	1.47	0.735	1.40	. . .	1.32	1.95	**. . .**
		433	. . .	1.60	0.730	. . .	. . .	1.31	3.04	**. . .**
		498	1.62	1.55	0.828	1.49	1.69	1.49	2.81	**1.86**
		626	1.96	1.87	1.03	2.01	. . .	1.85	200	**26.0**
Carbon spring steel, hardened and tempered	0.43	174	. . .	1.31	0.509	. . .	. . .	0.914	1.57	**. . .**
		344	1.47	1.44	0.626	. . .	. . .	1.12	1.87	**. . .**
		590	1.84	1.74	0.875	1.87	2.01	1.57	. . .	**. . .**
		688	1.75	1.85	0.968	1.87	1.87	1.74	∞	**113**
	0.74	221	. . .	1.42	0.645	1.45	. . .	1.16	1.96	**1.56**
		503	1.75	1.70	0.849	1.71	. . .	1.53	4.98	**2.24**
		650	2.03	1.86	0.950	2.35	2.19	1.70	∞	**69.4**
		813	2.51	2.32	1.18	3.07	2.93	2.12	∞	∞
Austenitic 18Cr-10Ni stainless steel	0.06	158	1.80	1.65	0.610	1.65	. . .	1.10	1.63	**. . .**

Armco ingot iron	**<0.02**	**100**	**1.00**	**1.00**	**0.378**	**1.00**	**1.00**	**0.680**	**1.00**	**1.00**

(a) Volumetric wear of reference material divided by volumetric wear of test material; reference material, Armco ingot iron.

(b) 1060 HV.

(c) 590 HV.

(d) $\text{HV}\mu/\text{HV}_a$, where $\text{HV}\mu$ is maximum Vickers hardness on abraded face and HV_a is Vickers hardness of abrasive.

In the example that follows, hardness appears to be a dominant factor governing the wear resistance of various materials in each specific application.

Example 1: Wear of Grinding Balls.

Performances of low-alloy martensitic steel grinding balls containing 0.80% C, 0.70% Mn, 0.30% Si, 0.20% Cr, 0.15% Mo, and 0.002% B (water quenched to 60 HRC) and pearlitic steel containing 0.80% C, 0.70% Mn, and 0.30% Si (oil quenched to give a fine pearlitic structure at 40 HRC) are compared in Fig. 4(a) and 4(b). Adding balls to a ball mill requires no shutdown time; therefore, selection is based on cost per pound compared with wear rate, as well as availability. The low-alloy martensitic balls cost more per pound, but their high wear resistance justifies the increased cost of these and numerous other grinding applications.

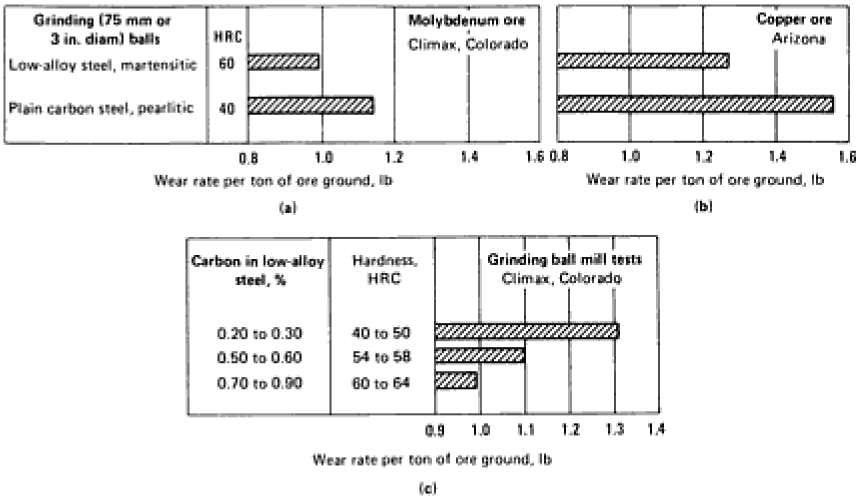


Fig. 4 Effect of steel composition, hardness, and type of material being ground on the wear rate of 75 mm (3 in.) diam steel grinding balls

In another series of tests, summarized in Fig. 4(c), three types of balls of fully hardened, low-alloy steel with varying carbon content were compared. Their compositions and hardnesses were as follows:

- *Low-carbon steel:* 0.25% C, 0.90% Mn, 0.30% Si, 0.60% Cr, 0.20% Mo, 0.002% B at 40 to 50 HRC
- *Medium-carbon steel:* 0.55% C, 0.90% Mn, 0.25% Si, 0.30% Cr, 0.05% Mo, 0.001% B at 54 to 58 HRC

- *High-carbon steel:* 0.80% C, 0.70% Mn, 0.30% Si, 0.20% Cr, 0.15% Mo, 0.002% B at 60 to 64 HRC

Lubrication and Lubricated Wear

Use of an effective lubricant can reduce wear in several ways. The lubricant serves to separate the rubbing surfaces, preventing or greatly reducing metal-to-metal contact. Complete separation is more readily achieved if the mating surfaces are smooth (except for microscopic asperities). The lubricant can also serve as a vehicle to remove loose wear debris from the rubbing areas before abrasive damage occurs. The lubricant, especially in a flowing system can control increases in temperature due to frictional heating.

Hydrodynamic lubrication occurs when the viscous property of a fluid during a shearing between two surfaces in relative motion produces sufficient fluid pressure to separate the surfaces and support a load. The hydrodynamic effect occurs when the fluid is forced to flow into a converging wedge configuration. In a journal bearing, this occurs when the rotating shaft surface drags a film of oil into a converging wedge formed by the displacement of the shaft center from the bearing center under applied load. Surface separation during hydrodynamic lubrication is sufficient to prevent any contact between asperities. Bearing friction is proportional to fluid viscosity and surface velocity. Minimum film thickness is proportional to viscosity and surface velocity. Hydrodynamic lubrication is also called "thick film" and "fluid film" lubrication.

Hydrostatic lubrication refers to a condition in which lubricant is supplied under sufficient pressure to separate the surfaces.

Elastohydrodynamic lubrication refers to the fluid film lubrication of high-speed rolling contacts. The contact area between the rolling elements is separated by a thin lubricant film (as small as 0.25 μm). Fluid dynamic conditions exist in the thin film. Under concentrated contact, such as a ball in contact with a race, a Hertzian pressure distribution is assumed to exist between the contact areas, and elastic deformation is assumed to cause a flattening in the contact zone. The fluid film is separated by approximately parallel surfaces. The entry condition in the hydrodynamic wedge and the elastically deformed region is one in which the fluid is subjected to high pressure and high shear rates. These conditions alter the apparent viscosity of the fluid (viscosity increases with pressure). Elastohydrodynamic lubrication requires very smooth surface finishes to prevent asperity contact.

Boundary lubrication denotes a range of contact conditions that occur when the hydrodynamic film collapses under high load or with too low a shear rate. Solid surface contact occurs between adsorbed soft surface films. The surface film can be an array of oriented long-chain fatty-acid molecules that have sufficient penetration resistance to prevent metal-to-metal contact. They also have a low shear resistance parallel to the surface, which allows sliding contact with reasonable friction levels (0.05 to 0.1 friction coefficient) and mild wear. Friction no longer becomes a function of viscosity or surface velocity. Boundary lubrication usually involves some metal-to-metal contact. A boundary film can be physically adsorbed or chemisorbed. The film is formed and replenished from the fluid lubricant environment. The success of boundary lubrication depends greatly on the surface chemistry of the lubricated surfaces and the operating conditions.

Solid lubrication describes a condition in which a soft solid is used instead of a fluid lubricant. The solid lubricant adheres to the rubbing surfaces and forms a low shear strength solid film. Natural solid lubricants include graphite and MoS_2. Once a solid film of lubricant becomes established, it tends to wear away unless continually replenished. The soft solid is suspended as a pigment in a resin or inorganic binder in solid lubricant coatings. Many of the effective solid lubricants have layer structures; however, this is not a prerequisite for classification as a solid lubricant.

Dry wear generally implies wear between surfaces without benefit of lubrication. Under certain conditions of load, speed, surface finish, and temperature, dry wear can occur even when a lubricant is present. Dry friction can lead to temperature increases that are sufficient to change microstructure and mechanical properties. Materials that achieve their hardness and strength by heat treatment are most likely to be affected by frictional heat. The actual surface temperatures achieved during dry wear are virtually impossible to measure, and both the temperatures themselves and the methods used to obtain them are matters of continuous controversy.

Selection of Steels for Wear Resistance

Wear problems are solved, wholly or in part, by the proper selection of metals. Stress analysis and laboratory investigation usually provide only a partial solution and seldom completely resolve wear problems. Frequently, a metal is selected for trial, shaped into an experimental or service part, incorporated in an operating mechanism, and observed for wear rate. If superior performance is proved in such limited service, the part may be incorporated in production models and run in varying conditions so further observations can be recorded on its life and suitability. Lubrication and design of contacting components also play important roles in wear control.

Mild steel demonstrates poor wear resistance and resistance to surface damage during dry sliding. The use of mild steel in sliding surface contact requires surface treatment, such as hardening or coating, and/or the selection of a "compatible" mating material such as bronze or babbitt. Where hard minerals comes in contact with steel, wear is very rapid unless the steel surface is hardened or coated with a very hard material.

Steel is subject to accelerated wear in a corrosive environment. Unprotected steel is also susceptible to fretting damage or formation of oxidized wear debris between two contacting surfaces in low-amplitude oscillating motion. A wide variety of microstructures are possible in the heat treatment of steel or cast iron. Wear properties can be related to specific microstructures.

Relative Costs. When selecting steel for wear resistance, the total cost of the steel and its heat treatment must be considered. The following steels, which may have suitable wear-resistance properties in specific applications, are listed in order of increasing total cost:

- *Low-carbon steels,* such as 1020, not heat treated
- *Simple high-carbon steels,* such as 1095, not heat treated
- *Directly hardened carbon or low-alloy steels,* either through hardened or surface hardened by induction or flame
- *Low-carbon or low-alloy steels* that are surface hardened by carburizing, cyaniding, or carbonitriding
- *Medium-carbon chromium or chromium-aluminum steels* that are hardened by nitriding
- *Directly hardened high-alloy steels,* such as D2 high-carbon, high-chromium tool steel (1.50% C, 12% Cr), that contain particles of free carbide
- *Precipitation-hardening stainless steels* (mainly for applications involving heat or corrosion, or both, as well as wear)
- *Specialty steels* produced by powder metallurgy or mechanical alloying techniques
- *Alloy carbides* bonded by steel matrices

Other ferrous materials, such as high-manganese austenitic steels and various classes of cast irons, are also widely used for wear-resistance applications (see the article "Wear-Resistant Austenitic Manganese Steels" in this Section).

Depth of Hardened Regions. Skids, grinding rods, chute liners, and similar parts may be considerably reduced in section before being replaced. In such parts, a more expensive deep-hardening steel may be more economical than a shallow-hardening steel. For example, a round bar 64 mm ($2\frac{1}{2}$ in.) in diameter with a surface hardness of 50 HRC may be made of either a water-quenched 1040 or an oil-quenched 5160 steel. However, by the time the bar has been worn to three-fourths of its original diameter (about 48 mm, or $1\frac{7}{8}$ in.), the 1040 steel will have a surface hardness of about 25 HRC and thus would wear at a much faster rate than the 5160 steel with its hardness of about 37 HRC at the same location.

Toughness. Wear resistance tends to increase with hardness, but it decreases as toughness increases. This is an important relationship in applications that require both wear resistance and impact resistance.

A correlation of wear resistance and toughness for a variety of ferrous alloys is shown in Fig. 5. The scatter arises, at least in part, from microstructural effects. For example, point 22B (Fig. 5) refers to AISI 4340 steel, quenched and tempered at a high temperature of about 650 °C (1200 °F) to produce fine carbides in a ferrite matrix. Point 22A represents the same steel, except it is normalized to produce fine pearlite; point 22C represents a quenched sample tempered at 205 °C (400 °F), a relatively low tempering temperature. Steels in the lower band of Fig. 5 combine toughness with wear resistance;

these are mainly the austenitic manganese steels. Figure 5 indicates that for most ferrous alloys there is a trade-off between wear resistance and toughness. In some alloys, altering carbon content is a simple way to adjust these properties.

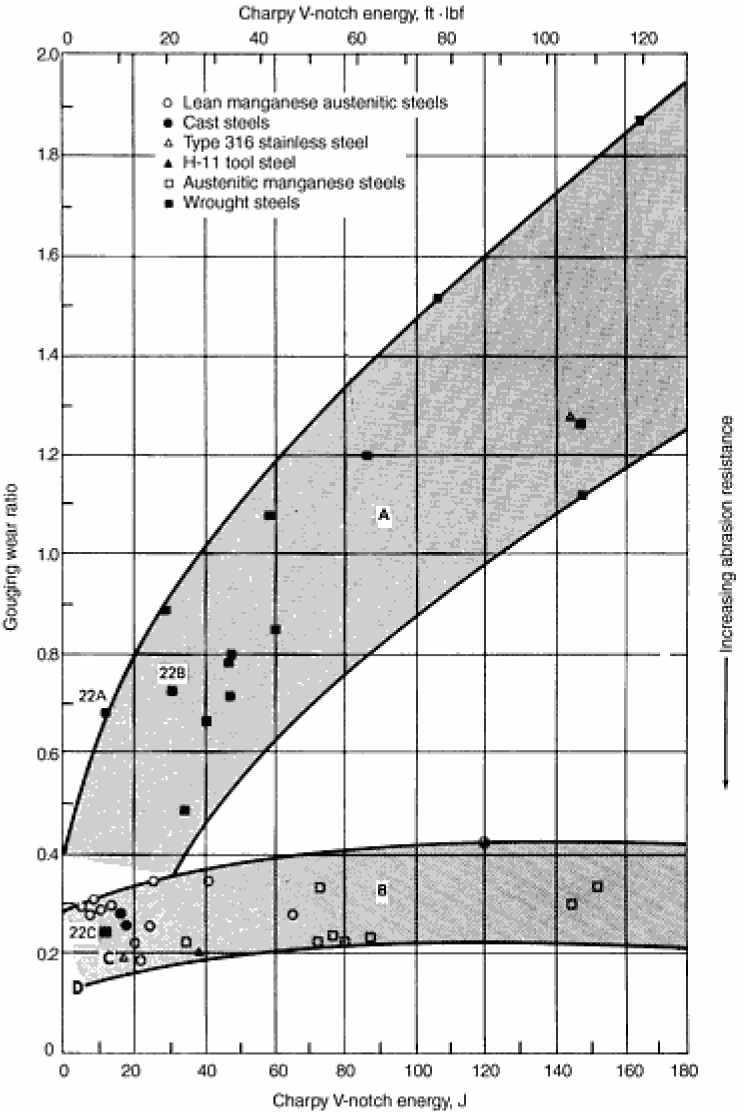


Fig. 5 Relationship between resistance to gouging abrasion and toughness of various materials. Area A, wrought and cast low-alloy steels; area B, austenitic manganese steels; area C, variety of heat-treated steels; area D, high-chromium white cast irons

Carbon Content. The wear resistance of ferritic steel is improved by hardening, either throughout the section or superficially. The maximum hardness depends on the carbon content of the steel and the amount of martensite (efficiency of quenching). This relationship is illustrated in the preceding article in this Section, "Hardenability of Carbon and Alloy Steels" (see Fig. 1).

Standard hardness measurements may indicate that a martensitic steel is largely transformed, although it may retain some austenite. Exposure to ultralow temperatures (followed by tempering) can help complete the transformation to martensite and improve wear resistance. Because martensite is a metastable structure, it begins to transform to more stable structures as the temperature is raised. Consequently, martensitic steels are not suitable for wear resistance at elevated temperatures or for applications in which the heat of friction can raise the temperature significantly. They should not be used at temperatures above 200 °C (390 °F). Special alloy steels, such as tool steels or martensitic stainless steels, are appropriate for service at higher temperatures. The thermal instability of martensite should also be considered during finishing operations (such as grinding), when a heat-affected zone could be produced at the surface. The resultant tempering effects could be localized or general; in either case, wear resistance is likely to be reduced.

Carbon content also affects hardness and wear resistance through the formation of various simple and complex carbides. Wear properties depend on the type, amount, shape, size, and distribution of carbides present, as well as the properties of the matrix (hardness, toughness, and stability). Despite this complexity, correlation of relative wear rates with carbon content is possible (see, for example, Fig. 6). Because most carbides are relatively stable compared to martensite, wear resistance achieved with the aid of these hard microconstituents is retained at higher temperatures.

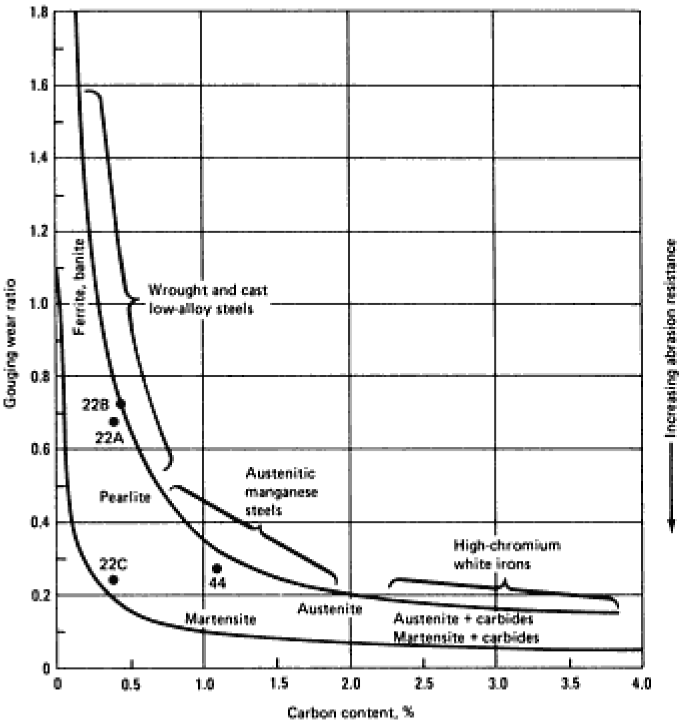


Fig. 6 Relation between gouging wear and carbon content for various types of steel and cast iron

Hardness and Microstructure. The frequent use of bulk hardness as a guide to abrasive wear resistance is supported by the data shown in Fig. 7 for annealed unalloyed metals. These data were obtained using abrasive cloth (two-body abrasion) with an abrasive hardness much greater than that of the metal samples. The data points are approximate; the experimental scatter of the measurements is not shown.

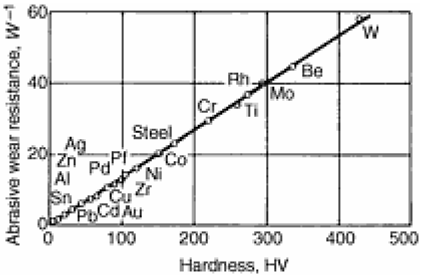


Fig. 7 Abrasive wear resistance versus hardness for annealed unalloyed metals and steel

Corresponding correlations with other properties related to hardness (such as elastic modulus) have also been presented. In all cases, if the metals are unalloyed, a simple correlation is obtained for controlled tests of two-body abrasion. Different crystal structures would be expected to yield different correlations, but the data in Fig. 7 do not show such an effect.

Care must be exercised in extending the simple hardness correlation to metals containing impurities or solutes, or to more complicated alloys. Figure 8 shows how wear resistance and hardness correlate for various classes of materials. The linear plot shown for pure metals in Fig. 7 is repeated as the steep line in Fig. 8. Another straight line describes brittle ceramics reasonably well. The differences in bonding type may account for these two distinct lines.

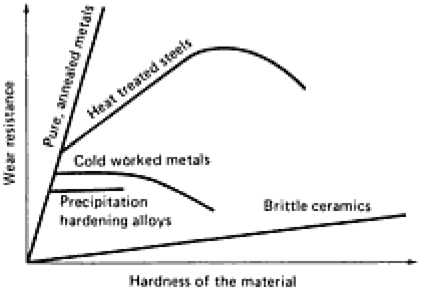


Fig. 8 Schematic representation of the correlation between wear resistance and hardness of different materials in various microstructural conditions

Wear and Microstructure

The preceding discussion established the importance of hardness and microstructure as factors in resistance to wear. Metallurgically, hardness and microstructure are commonly interrelated. Increasing the carbon content of a carbon steel, for example, results in microstructural alteration that increases as-quenched hardness and decreases ductility or toughness.

Wear Resistance at Constant Hardness. Very few tests of the comparative wear resistance of different steels at a constant hardness have been reported. However, in one series of tests for seizure resistance under heavy loads, a variety of steels were selected to provide a wide range of mechanical properties and microstructures when heat treated to 40 HRC. The steels, which are listed in Table 3, include a plain carbon steel, a tool steel, an alloy steel, a martensitic stainless steel, two precipitation-hardening steels, and a maraging steel. Details of heat treatment and a description of the various microstructures are also given in Table 3.

Table 3 Steels used in seizure-resistance tests

Type of Steel	**Type of heat treatment**	**Details of heat treatment**	Description of structure
1040	Quenched and tempered	830 °C (1525 °F), 20 min, WQ; 415 °C (780 °F), 4 h, AC	**Tempered martensite with very fine carbide distribution**
W1 (I)	Quenched and tempered	790 °C (1455 °F), 20 min, WQ; 440 °C (825 °F), 4 h, AC	**Tempered martensite with very fine carbide distribution**
W1 (II)	Quenched and tempered	900 °C (1650 °F), 20 min, OQ; 470 °C (880 °F), 4 h, AC	**Primary carbides (4 to 8 μm) in tempered martensite matrix**
4340	Quenched and tempered	830 °C (1525 °F), 20 min, OQ; 485 °C (905 °F), 4 h, AC	**Tempered martensite with very fine carbide distribution**
440C	Quenched and tempered	1065 °C (1950 °F), 20 min, OQ; 580 °C (1075 °F), 2 h, AC	**Large primary Cr and Fe carbides (20 μm) in tempered martensitic matrix**

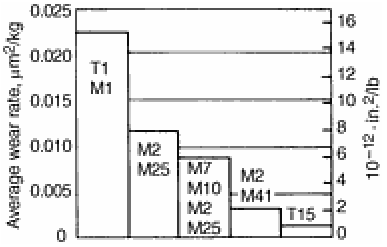
15-5 PH	Solution treated and aged	1040 °C (1905 °F), 30 min, OQ; 530 °C (985 °F), 4 h, AC	**Martensite**
17-4 PH	Solution treated and aged	1040 °C (1905 °F), 30 min, OQ; 530 °C (985 °F), 4 h, AC	**δ-ferrite stringers in martensitic matrix**
18Ni (250) (I)	Solution treated and underaged	815 °C (1500 °F), 60 min (in vacuum), AC; 320 °C (610 °F), 2 h, AC	**Lath martensite**
18Ni (250) (II)	**Solution treated and overaged**	**815 °C (1500 °F), 60 min (in vacuum), AC; 630 °C (1165 °F), 2 h, AC**	**Lath martensite and very fine reverted austenite**

Note: WQ, water quenched; OQ, oil quenched; AC, air cooled. Source: Ref 12

Effect of Carbides on Wear. The amount, size, and distribution of carbides in a steel microstructure have a distinct influence on wear resistance. For the most part, wear resistance increases as the amount or size of carbide particles at the wear surface increases. This effect is most often attributed to the proportion of the surface area occupied by the carbides and is more pronounced when gouging abrasion is not a factor. The following examples illustrate the effect of carbides in various wear applications.

Example 2: Influence of Amount of Carbides on Wear of High-Speed Tool Steels.

Specimens of several different high-hardness, high-speed tool steels were tested in a crossed-cylinder sliding wear machine. The fixed cylinder was made of tungsten carbide (6% Co), rotating at 40,000 rev/h, with an applied load of 68 kg (15 lb). Sliding distances ranged from 1×10^{-5} to 5×10^{-5} in. Bulk hardness values of all four steels were in the narrow range of 65 to 67.5 HRC. However, wear rates varied considerably, as shown in Fig. 9. The dominant factor seems to have been the content of hard MC-type vanadium carbide (2800 HK), which was highest in the T15 steel and lowest in the T1 and M1 steels.



Type or grade	**Composition, %**		**Total carbide**	**MC-type carbide**	Hardness, HRC
	C	**V**			
T1,M1	0.75	1	29	2	**65**
M2,M25	0.85	2	28	3	**65**
M7,M10, M2,M25	1.10	2	26	4	**66**
M2,M41	1.1	2	28	4.5	**67.5**

Fig. 9 Wear rates for high-speed steels

Reference cited in this section

12. P.E. Waudby, Rare Earth Additions to Steel, *Int. Met. Rev.*, Review 229, No. 2, 1978, p 74-98

Hardness Evaluation

With some exceptions, the data in this article have indicated that hardness is the most significant factor in controlling wear of steel. Conventional methods of hardness evaluation such as Rockwell and Brinell tests may not always provide sufficient information or may be insensitive to minor, but significant, aberrations. Small amounts of retained austenite, decarburization or variation in microconstituents, and other factors that are not always evaluated in conventional hardness tests may have a marked influence on wear resistance.

Microhardness testing is more effective for detecting local differences. Hardness traverses taken on polished cross sections may reveal conditions not registered by other means.

Elevated-Temperature Properties of Steels

CARBON AND LOW-ALLOY STEELS are used extensively at elevated temperatures in fossil-fired power-generating plants, aircraft power plants, chemical-processing plants, and petroleum-processing plants. The term "elevated temperature" can be used to mean any temperature above room temperature. As applied to the carbon and low-alloy chromium-molybdenum (Cr-Mo) steels considered in this article, elevated temperature relates primarily to the temperature range of almost 370 to 650 °C (700 to 1200 °F). The properties of carbon and Cr-Mo steels vary considerably over this temperature range.

Some devices, such as steam power plants and gas turbines, operate with increasing efficiency as the operating temperature is raised. The maximum temperature at which such equipment can operate is limited by the capabilities of materials from which it is made. Resistance of steels to degradation of properties at elevated temperatures usually increases with alloy content; the cost of these steels also increased with alloy content. Thus, selection of steels to be used at elevated temperatures generally involves a compromise between the higher efficiencies obtained at higher operating temperatures and the cost of the equipment, including materials, fabrication, replacement, and down-time costs.

Carbon Steels

Carbon steels are widely used in pressure vessel fabrication because of their low cost, versatile mechanical properties, and availability in fabricated forms. They are the most common materials used in noncorrosive environments in the temperature range of -29 to 425 °C (-20 to 800 °F) in oil refineries and chemical plants. Although the ASME Boiler and Pressure Vessel Code (BPVC) gives allowable stresses for temperatures greater than 425 °C (800 °F), it also notes that prolonged exposure at these temperatures may result in the carbide phase of the carbon steel being converted to graphite. This phenomenon, known as "graphitization," is a cumulative process dependent on the time the material is at or above 425 °C (800 °F). The result is a weakening of the steel after high-temperature exposure. Carbon steels are also increasingly affected by creep at temperatures above 370 °C (700 °F).

Heat-Resistant Cr-Mo Steels

The Cr-Mo steels are preferred in the construction of high-temperature components because they possess excellent strength, toughness, and corrosion resistance relative to carbon steels and most low-alloy steels. Components fabricated from Cr-Mo steels serve in the petroleum, petrochemical, fossil power, and pulp and paper industries. The steels are most often used at temperatures of 316 °C (600 °F) and higher, when creep effects, graphitization, or hydrogen attack may be significant in carbon steels.

Like most steels, the Cr-Mo steels respond to heat treatment, and a single composition may be produced in several strength classes. The low-chromium Cr-Mo steels have moderate hardenability. Slow cooling and isothermal annealing during cooling produce ferrite-pearlite microstructures that have long-time stability but relatively low tensile strength and toughness. Rapid air cooling and enhanced cooling produce bainitic steels, which tend to be stronger and tougher. Medium-chromium Cr-Mo steels have moderate hardenability, and air cooling is generally sufficient to produce bainite through-thicknesses of 150 mm (6 in.) and more. The bainitic steels are usually tempered. The high-chromium Cr-Mo steels have excellent hardening ability, and air cooling is sufficient to produce martensite through most thicknesses. Accelerated cooling of the steels is permitted, but care must be taken to avoid cracking. The martensitic steels are always tempered.

Compositions and Metallurgy. Nominal compositions for the heat-resistant, Cr-Mo steels are provided in Table 4. The steels range from $\frac{1}{2}$ to 12% Cr and $\frac{1}{2}$ to 1% Mo. Product forms include tubes, pipes, forgings, fittings, plates, and castings. Welded tubing and pipes are included. Depending on the product, the maximum use temperature for pressure-boundary applications ranges from 480 to 650 °C (900 to 1200 °F).

Table 4 Summary of Cr-Mo steels used in high-temperature service

Nominal composition	**ASTM specification**	**Product form**	**UNS numbers**	**Minimum or range of ultimate strength**		**Minimum yield strength**		Maximum use temperature	
				MPa	**ksi**	**MPa**	**ksi**	**°C**	°F
$\frac{1}{2}$Cr-$\frac{1}{2}$Mo	A 335 P2	Tube	K11547, K12143	380	55	205	30	540	**1000**
	A 230 T2	Tube	K11547	414	60	205	30	540	**1000**
	A 182 F2	Forgings	K12122	485	70	275	40	540	**1000**
1Cr-$\frac{1}{2}$Mo	A 387 Gr12/Cl1	Plate	K11757	380-550	55	220	33	650	**1200**
	A 213 T12	Tube	K11562, K12062	415	60	220	32	650	**1200**
	A 387 Gr12/Cl2	Plate	K11757	450-585	65	275	40	650	**1200**
	A 182 F12/Cl2	Forgings	K11564	485	70	275	40	650	**1200**
1$\frac{1}{4}$Cr-$\frac{1}{2}$Mo-Si	A 182 F11/Cl1	Forgings	K11597	415	60	205	30	650	**1200**
	A 387 Gr11/Cl1	Plate	K11789	415-585	60	245	35	650	**1200**
	A 187 F11/Cl2	Forgings	K11572	485	70	275	40	650	**1200**
	A 387 Gr11/Cl2	Plate	K11787	515-690	75	310	45	650	**1200**
2$\frac{1}{4}$Cr-1Mo	A 182 F22	Forgings	K21590	415	60	205	30	650	**1200**
	A 217 WC9	Castings	J21890	485-655	70	275	40	650	**1200**
	A 182 F22/Cl3	Forgings	K21590, K21390	515	75	310	45	650	**1200**
2$\frac{1}{4}$Cr-1Mo-$\frac{1}{4}$V	A 182 F22V	Forgings	K31835	585-760	85	415	60	480	**900**
2$\frac{1}{4}$Cr-1.6W	A 213 T23	Tube	. . .	510	74	400	58	650	**1200**
3Cr-1Mo	A 199 T21	Tube	K31545	415	60	170	25	650	**1200**

	A 213 T21	Tube	K31545	415	60	205	30	650	**1200**
	A 336 F21/Cl3	Forgings	K31545	515	75	310	45	650	**1200**
3Cr-1Mo-$\frac{1}{4}$V-Ti-B	A 182 F3V	Forgings	K31830	585-760	85	415	60	480	**900**
5Cr-$\frac{1}{2}$Mo	A 213 T5	Tube	K41545	415	60	205	30	650	**1200**
	A 336 F5A	Forgings	K42544	550-725	80	345	50	650	**1200**
	A 182 F5a	Forgings	K42544	620	90	450	65	650	**1200**
5Cr-$\frac{1}{2}$Mo-Si	A 213 T5b	Tube	K51545	415	60	205	30	650	**1200**
5Cr-$\frac{1}{2}$Mo-Ti	A 213 T5c	Tube	K41245	415	60	205	30	650	**1200**
9Cr-1Mo	A 213 T9	Tube	K81590, K90941	415	60	205	30	650	**1200**
	A 182 F9	Forgings	K81590	585	85	380	55	650	**1200**
	A 212	Castings	J82090	620	90	415	60	650	**1200**
9Cr-1Mo-V	A 182 F91	Forgings	S50460	585	85	415	60	650	**1200**
9Cr-2W	A 213	Tube	. . .	620	90	440	64	650	**1200**
12Cr-2W	**A 213**	**Tube**	**. . .**	**620**	**90**	**400**	**58**	**650**	**1200**

The $\frac{1}{2}$Cr-$\frac{1}{2}$Mo steel is produced to three strength levels and is approved in the ASME BPVC for service to 540 °C (1000 °F). The 1Cr-$\frac{1}{2}$Mo and 1$\frac{1}{4}$Cr-$\frac{1}{2}$Mo steels are produced in three strength levels and are approved for service to 650 °C (1200 °F). The 1$\frac{1}{4}$Cr-$\frac{1}{2}$Mo steel is the most widely used of the Cr-Mo steels, but the greatest body of information is available for 2$\frac{1}{4}$Cr-1Mo steel. Wrought 2$\frac{1}{4}$Cr-1Mo steel is produced to several strength levels. The annealed steel (class 1) has a largely ferrite-pearlite microstructure, although bainite is often present. The class 1 steel is used in the power industry as superheater/reheater tubing, headers, and main steam line piping for service temperatures to 650 °C (1200 °F). The normalized-and-tempered steel (class 2) is used for heavy-wall pressure vessels in the petroleum and petrochemical industries for temperatures to 480 °C (900 °F). In Europe and Asia, the class 2 material is often used for tubing and piping in the power industry for service to 650 °C (1200 °F). Quenched-and-tempered versions of 2$\frac{1}{4}$Cr-1Mo steels exist. These steels are intended for heavy-wall pressure vessels but are limited to service at temperatures below the creep range because of their susceptibility to hydrogen attack. The 3Cr-1Mo steel is available in two strength levels and has strength properties comparable to those of 2$\frac{1}{4}$Cr-1Mo steel, but improved resistance to hydrogen attack.

Recently, $2\frac{1}{4}$Cr-1Mo and 3Cr-1Mo steels with vanadium additions have been commercially developed for high-temperature pressure vessels and piping. The vanadium-bearing steels have better strength and are more resistant to hydrogen attack than steels without vanadium additions. The use of vanadium-modified $2\frac{1}{4}$Cr-1Mo steel and 3Cr-1Mo steel has been for heavy-wall pressure vessels. Further modifications of the 3Cr-1Mo-$\frac{1}{4}$V steels have been produced by adding titanium, niobium, calcium, and the like. The strength and toughness of the steels are comparable to that of the steels listed in Table 4.

The straight 9Cr-1Mo steel is approved for service in the BPVC to 650 °C (1200 °F), but usage has not been widespread. However, the 9Cr-1Mo-V steel developed in the late 1980s has been installed as tubing, piping, forgings, and castings in a variety of applications for the power, petroleum, and petrochemical industries and has accumulated up to 15 years of exposure at temperatures in the creep regime.

Even more recently, tungsten has been used as a replacement for some of the molybdenum to improve the weldability and toughness of Cr-Mo steels. Three steels included in the grouping include a $2\frac{1}{4}$Cr-1.6W steel, a 9Cr-2W steel, and a 12Cr-2W steel. The tungsten-bearing steels contain $\frac{1}{2}$% Mo and $\frac{1}{4}$% V, and they are intended for superheater/reheater tubing and piping for steam lines.

Mechanical Properties at Elevated Temperatures

The allowable design stresses for steels at elevated temperatures may be controlled by different mechanical properties, depending on the application and temperature exposure. For applications with temperatures below the creep-temperature range, tensile strength or yield strength at the expected service temperature generally controls allowable stresses. For temperatures in the creep range, allowable stresses are determined from either creep-rupture properties or the degree of deformation from creep. In recent years, the worldwide interest in life extension of high-temperature components has also promoted considerably more interest in elevated-temperature fatigue. This effort has led to tests and methods for evaluating the effects of creep-fatigue interaction on the life of elevated-temperature components.

Ductility and toughness may also be important considerations, although ductility and toughness considerations usually do not enter directly into the setting of allowable stresses. In elevated-temperature applications, ductility and toughness might not remain fixed in magnitude or character and often change with temperature and with time at temperature. The changes, which may be beneficial but often are deleterious, are of interest both at service temperature and, because of shutdowns, at ambient temperatures. Ductility is also an important factor that influences notch sensitivity and creep-fatigue interaction.

The types of tests most commonly used to evaluate the mechanical properties of steels at elevated temperatures include:

- Short-term elevated-temperature tests
- Long-term elevated-temperature tests
- Short-term and long-term tests following long-term exposure to elevated temperatures
- Fatigue tests (including thermal fatigue and thermal shock tests)
- Time-dependent fatigue tests

Short-term elevated temperature tests include the elevated-temperature tensile tests (described in ASTM E 21), a test for elastic modulus (ASTM E 231), compression tests, pin bearing load tests, and the hot hardness test. The mechanical properties determined by means of the tensile test include ultimate tensile strength, yield strength, percent elongation, and percent reduction in area. Because elevated-temperature tensile properties are sensitive to strain rate, these tests are conducted at carefully controlled strain rates. Tensile strength data obtained on specimens of annealed $2\frac{1}{4}$ Cr-1Mo steel at various temperatures and at strain rates ranging from 2.7×10^{-6} s^{-1} to 144 s^{-1} are shown in Fig. 10.

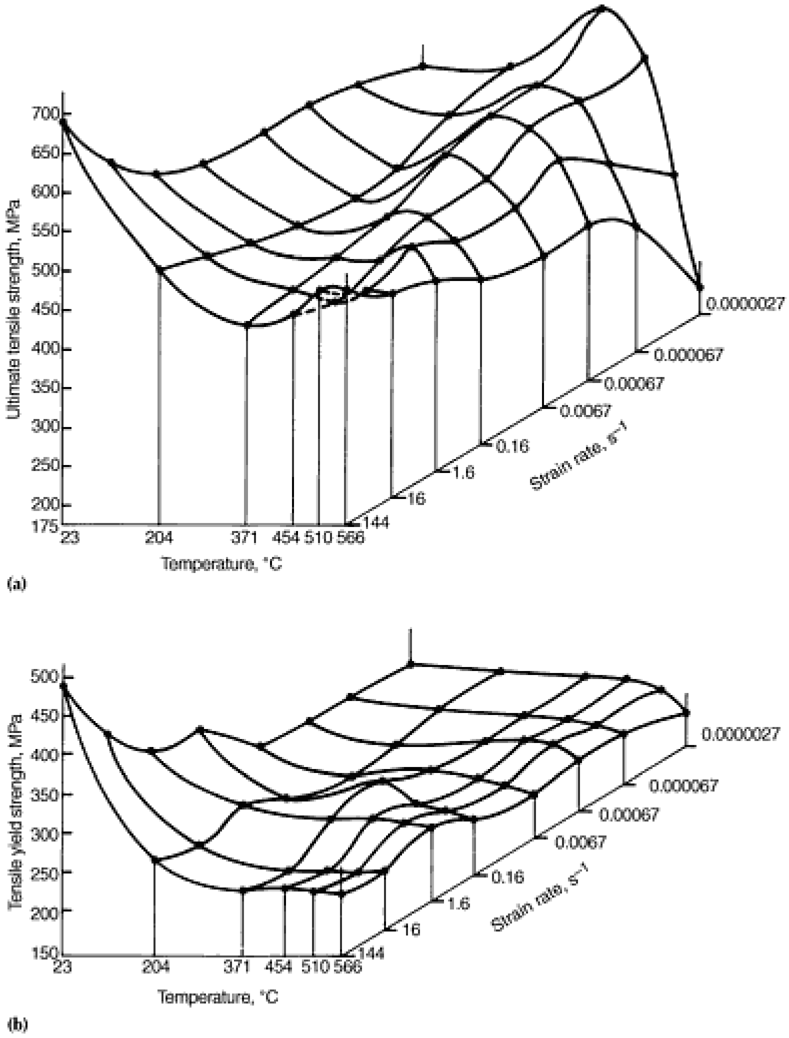


Fig. 10 Effect of test temperature and strain rate on the strength of annealed $2\frac{1}{4}$ Cr-1 Mo steel. Tensile strength (a) and yield strength (b) of $2\frac{1}{4}$ Cr-1 Mo steel tested at various temperatures and strain rates

In designing components that are to be produced from low-alloy steels and to be exposed to temperatures up to 370 °C (700 °F), the yield and ultimate strengths at the maximum service temperature can be used much as they would be used in the design of components for service at room temperature. Certain codes require that appropriate factors be applied in calculating allowable stresses.

Elevated-temperature values of elastic modulus can be determined during tensile testing or dynamic testing by measuring the natural frequency of a test bar at the designated test temperature. Figure 11 shows values of elastic modulus at temperatures between room temperature and 650 °C (1200 °F) for several low-alloy steels, determined during static tensile loading and dynamic loading.

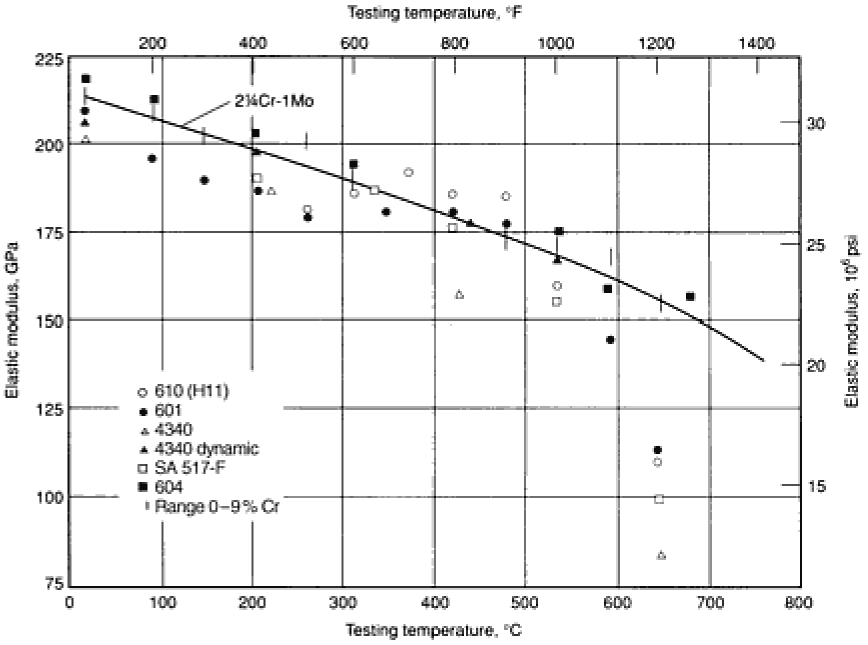


Fig. 11 Effect of test temperature on elastic modulus for several steels commonly used at elevated temperatures. Dynamic measurements of elastic modulus were made by determining the natural frequencies of test specimens; static measurements were made during tensile testing.

Compression tests and pin bearing load tests (ASTM E 209 and E 238) can be used to evaluate materials for applications in which the components will be subjected to these types of loading at elevated temperatures. Hot hardness tests can be used to evaluate materials for elevated-temperature service and can be applied to the qualification of materials in the same way in which room-temperature hardness tests are applied.

Components for many elevated-temperature applications are joined by welding. Elevated-temperature properties of both the weld metal and the heat-affected zones can be determined by the same methods used to evaluate the properties of the base metal.

Long-term elevated-temperature tests are used to evaluate the effects of creep, which is defined as the time-dependent strain that occurs under constant load at elevated temperatures. Creep is observed in steels at temperatures above about 370 °C (700 °F). In general, creep occurs at a temperature slightly above the recrystallization temperature of a metal or alloy; at such a temperature, atoms become sufficiently mobile to allow time-dependent rearrangement of the structure. In time, creep may lead to excessive deformation and even fracture at stresses considerably below those determined in room-temperature and elevated-temperature short-term tension tests.

Typical creep behavior consists of three distinct stages as shown in Fig. 12. Following initial elastic-plastic strain resulting from the immediate effects of the applied load, there is a region of increasing plastic strain at a decreasing strain rate (first-stage, or primary, creep). Following the primary creep region, there is a region where the creep strain increases at a minimum, and almost constant, rate of plastic strain (second-stage, or secondary creep). This nominally constant creep rate is generally known as the minimum creep rate and is widely employed in research and engineering studies. Finally, there is a region of drastically increased strain rate with rapid extension to fracture (third-stage, or tertiary creep). Tertiary creep has no distinct beginning, but does refer to the region with an increasing rate of extension that is followed by fracture.

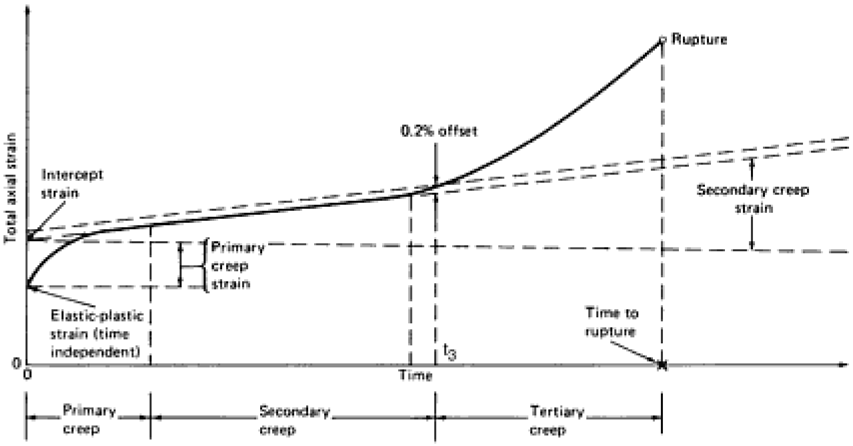

Rupture
0.2% offset
Intercept strain
Total axial strain
Secondary creep strain
Primary creep strain
Elastic-plastic strain (time independent)
Time to rupture
t_3
0
0
Time
Primary creep
Secondary creep
Tertiary creep

Fig. 12 Schematic representation of classical creep behavior

Of all the parameters pertaining to the creep curve, the most important for engineering applications are the creep rate and the time to rupture. These parameters are determined from long-term elevated-temperature tests that include creep, creep-rupture, and stress-rupture tests (ASTM E 139) and notched-bar rupture tests (ASTM E 292). In addition, relaxation tests (ASTM E 328) are used to evaluate the effect of creep behavior on the performance of high-temperature bolt steels.

When the rate or degree of deformation is the limiting factor, the design stress is based on the minimum (secondary) creep rate and design life after allowing for initial transient creep. The stress that produces a specified minimum creep rate of an alloy or a specified amount of creep deformation in a given time (for example, 1% total creep in 100,000 h) is referred to as the limiting creep strength or limiting stress. Typical creep strengths of various low-alloy steels are shown in Fig. 13.

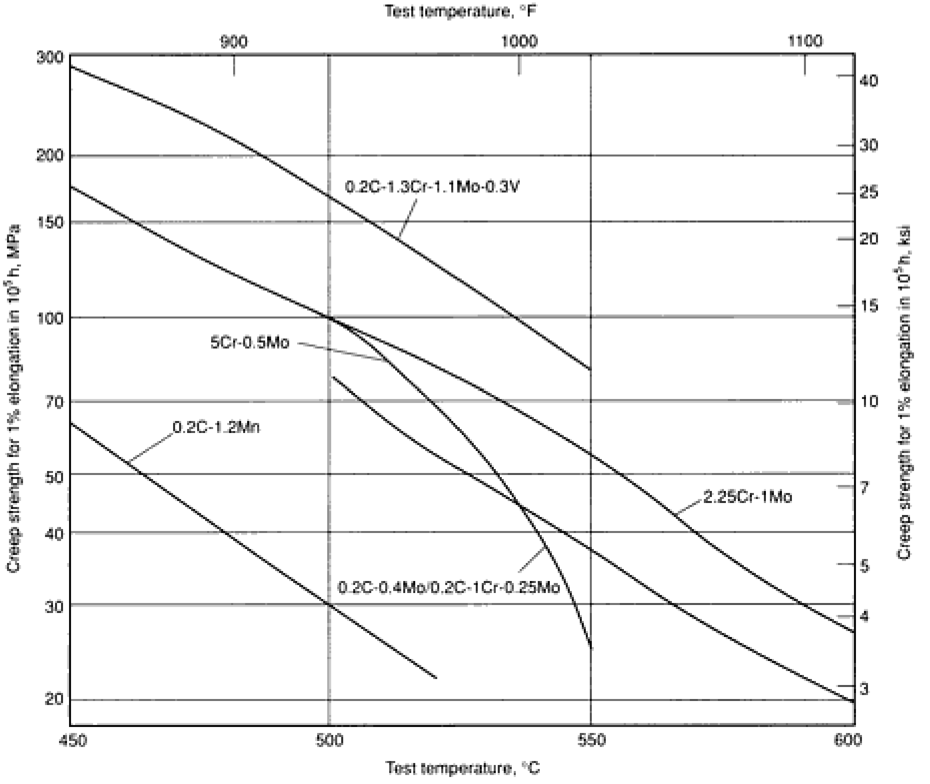


Fig. 13 General comparison of creep strengths of carious creep-resistant low-alloy steels

When fracture is a limiting factor, stress-rupture values are used in design. Stress-rupture values of various low-alloy chromium-molybdenum steels are shown in Fig. 14.

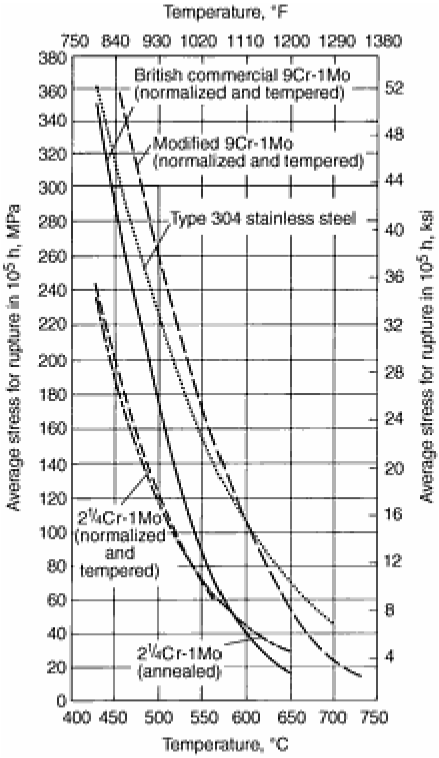


Fig. 14 Variation of 100,000 h creep-rupture strength as a function of temperature for $2\frac{1}{4}$Cr-1Mo steel, standard 9Cr-1Mo, modified 9Cr-1Mo, and 304 stainless steel

For those alloys in which failure occurs before a well-defined start of tertiary creep, it is useful to use notched specimens or specimens with both smooth and notched test sections (with the cross-sectional area of the notch equal to that of the smooth test section). If the material is notch sensitive, the specimen will fail in the notch before failure occurs in the smooth section. It has been well recognized for many years that notch sensitivity is related to creep ductility. It has been suggested that a minimum smooth-bar creep ductility of about 10% in terms of reduction in area may be desirable for avoidance of notch sensitivity. Limited published data on notched stress-rupture properties of low-alloy ferritic steels for elevated temperatures indicate that these steels generally are not notch sensitive. Representative stress-rupture data for notched and unnotched specimens of 17-22 AV steel (Fe-0.27C-0.75Mn-0.65Si-1.25Cr-0.50Mo-0.85V) are presented in Fig. 15.

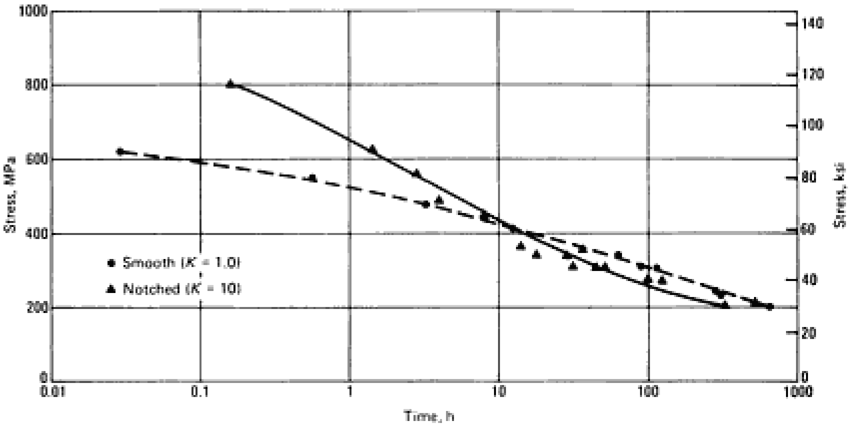


Fig. 15 Effect of notch on stress-rupture behavior. Stress-rupture behavior of smooth (K = 1.0) and notched specimens of Fe-0.27C-0.75Mn-0.65Si-1.25Cr-0.50Mo-0.85V steel tested at 595 °C (1100 °F). All specimens were normalized at 980 °C (1800 °F) and tempered at 6 h at 675 °C (1250 °F)

Long-term exposure to elevated temperature may affect either short-term or long-term properties. For example, exposure of plain carbon steels to elevated temperatures (such as 650 °C, or 1200 °F) can cause overtempering or spheroidization, Such a change in microstructure can logically be expected to change the mechanical properties of the steel. Other metallurgical instabilities may affect the mechanical properties of steels. For example, long-term exposure of Cr-Mo steel can result in an evolution of the carbide structure resulting in coarsening of the carbides, changes in the matrix composition, and an overall decrease in creep strength.

Long-term exposure to elevated temperature may also affect the properties of steels through alteration of the steel by the environment. Carbon steels are subject to oxidation in air, and the cross-sectional area of a steel part may be reduced by flaking away of surface oxide. Long-term exposure to carbon-bearing or sulfur-bearing atmospheres will result in carbon or sulfur pickup; after such exposure, the steel can be expected to have different properties.

Thermal shock tests may be used to determine the effects of rapid changes in temperature on the properties of steel parts. Thermal shock can occur as the result of a single change in temperature (quench cracking, for example), or as the result of cyclic variations in temperature such as those experienced by heat treating fixtures.

Time-Dependent Fatigue Tests. Creep and relaxation data are obtained at constant temperatures and either constant-load or constant-strain conditions. However, in many service applications, cyclic variations in either temperature or applied stress, (or strain) can occur. These variations may occur randomly or in regular, uniform cycles. In order to determine the effect of cyclic loading superimposed on a constant load at elevated temperatures, several types of fatigue testing may be employed: constant alternating stress, constant alternating strain, tension-tension loading with the stress ratios greater than zero, and special waveforms that provide specific holding times at maximum load. Results of these tests show what factors are most contributory to deformation and fracture of the specimens for the testing conditions employed. A more detailed account of the complex interactions of creep and fatigue can be found in the *ASM Specialty Handbook: Heat-Resistant Materials.*

Data Presentation and Analysis

The behavior of steels at elevated temperatures can be affected by many variables, some of which are time, temperature, stress, and strength. Attempting to analyze so many variables is difficult. Presentation of the data is difficult also. A variety of methods for correlating, interpolating, and extrapolating elevated-temperature mechanical-property data have been devised. Appropriate texts, such as *Mechanical Testing,* Vol 8, *ASM Handbook,* should be consulted.

One method for comparing steels of different strengths is to report elevated-temperature strength as a percentage of room-temperature strength; this method is illustrated in Fig. 16. The strength levels of the steels represented in Fig. 16 varied from 480 to 1100 MPa (70 to 160 ksi).

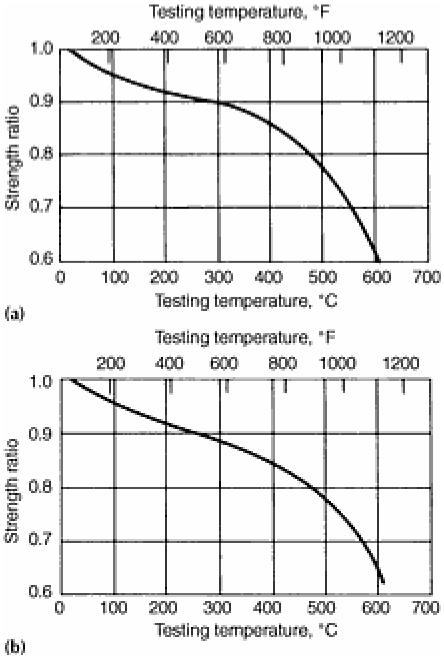


Fig. 16 Ratios of elevated-temperature strength to room-temperature strength for hardened-and-tempered $2\frac{1}{4}$ Cr-1Mo steel tempered to room-temperature tensile strengths ranging from 480 to 1100 MPa (70 to 160 ksi). (a) Tensile strength. (b) Yield strength

Four different presentations of the same creep data for $2\frac{1}{4}$ Cr-1Mo steel are given in Fig. 17. In parts (a), (b), and (c), only the creep strain is plotted. In the isochronous stress-strain diagram (part d), total strain is used. The over-all format of Fig. 17(d) is particularly useful in design problems where total strain is a major consideration; the linear scales make unjustified extrapolation a little more difficult.

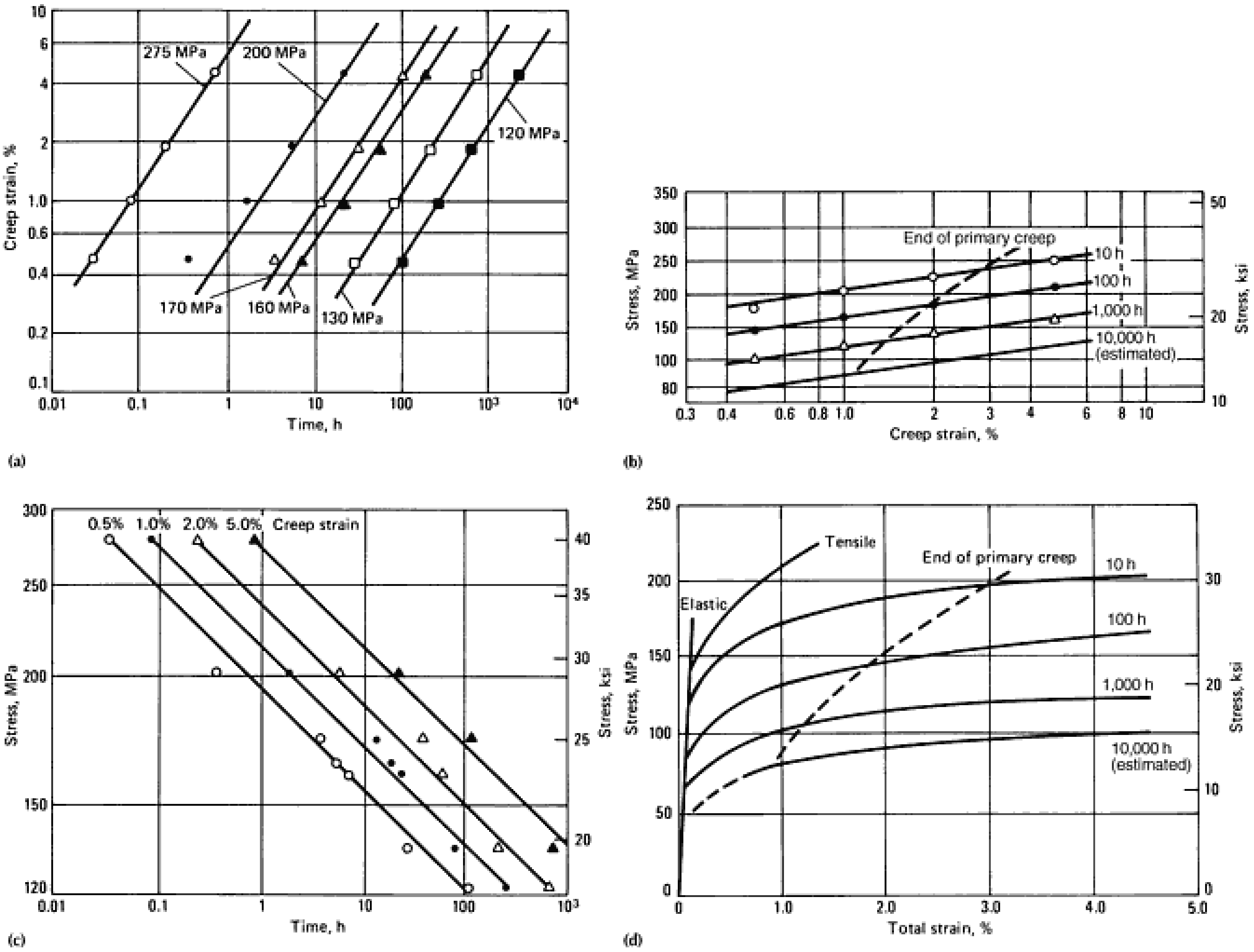


Fig. 17 Analysis of creep data. Creep behavior of $2\frac{1}{4}$ Cr-1Mo steel tested at 540 °C (1000 °F). (a) Creep strain-time plot; constant-stress lines have been drawn parallel. (b) Stress-creep strain plot. (c) Stress-time plot; constant-strain lines have been drawn parallel. (d) Isochronous stress-strain curves

Effects of Composition

The mechanical properties of carbon and low-alloy steels are determined primarily by composition and heat treatment. The effects of alloying elements in annealed, normalized and tempered, and quenched and tempered steels are discussed below.

Carbon increases both the strength and hardenability of steel at room temperature but decreases the weldability and impact toughness. In plain carbon and carbon-molybdenum steels intended for elevated-temperature service, carbon content is usually limited to about 0.20%. In some classes of tubing for boilers, however, carbon maybe as high as 0.35%. For chromium-containing steels, carbon content is usually limited to 0.15%. Carbon increases short-term tensile strength but does not add appreciably to creep resistance at temperatures above 540 °C (1000 °F), because carbides eventually become spheroidized at such temperatures.

Manganese, in addition to its normal function of preventing hot shortness by forming dispersed manganese sulfide inclusions, also appears to enhance the effectiveness of nitrogen in increasing the strength of plain carbon steels at elevated temperatures. Manganese significantly improves hardenability but contributes to temper embrittlement.

Phosphorus and sulfur are considered undesirable because they reduce the elevated-temperature ductility of steel. This reduction in ductility is demonstrated by reductions in stress-rupture life and thermal fatigue life. Phosphorus contributes to temper embrittlement.

Silicon increases the elevated-temperature strength of steel. It also increases the resistance to scaling of the low-chromium steels in air at elevated temperatures.

Chromium in small amounts (~0.5%) is a carbide former and stabilizer. In larger amounts (up to 9% or more), it increases the resistance of steels to corrosion. Chromium also influences hardenability.

The effect of chromium in creep-resistant Cr-Mo steels is complex. By itself, chromium enhances creep strength, although increasing the chromium content in lower-carbon grades does not increase resistance to deformation at elevated temperatures. When added to molybdenum steel, chromium generally leads to some reduction in creep strength, such as that shown in Fig. 18. For the 1Mo steel in Fig. 18, the optimum creep strength occurs with about 2.5% Cr. Chromium is most effective in strengthening molybdenum steels (0.5 to 1% Mo) when it is used in amounts of 1 to 2.5%.

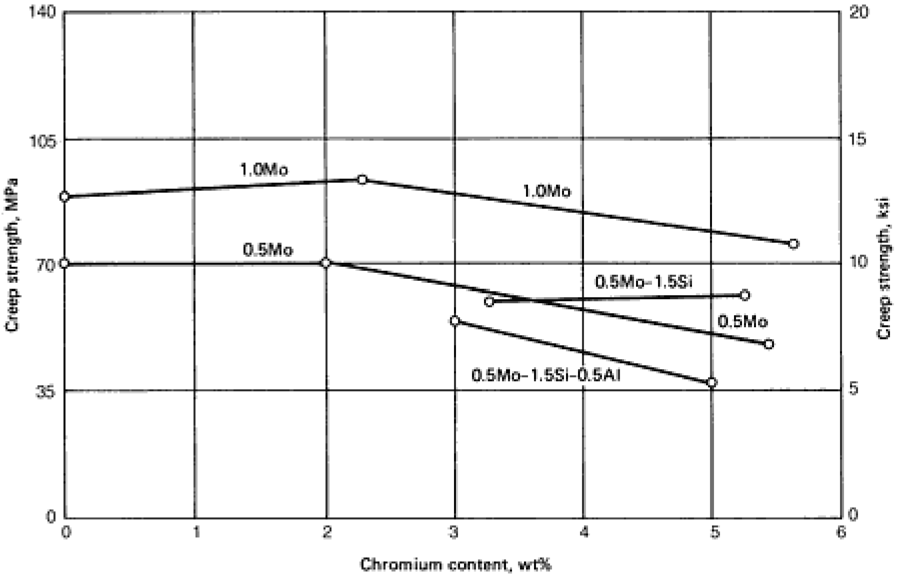


Fig. 18 Effect of chromium on the creep strength (stress to produce a minimum creep rate of 0.0001% per hour) of several steels containing small amounts of molybdenum, silicon, and aluminum at 540 °C (1000 °F)

Molybdenum is an essential alloying element in heat-resistant steels where good creep resistance above 450 °C (840 °F) is required. Even in small amounts (0.1 to 0.5%), molybdenum increases the resistance of these steels to deformation at elevated temperatures. Much greater creep strength can be obtained by increasing the molybdenum level to about 1%, but at the expense of greatly reduced rupture ductility. Additions of chromium can improve rupture ductility.

Molybdenum is a carbide stabilizer and prevents graphitization. For certain ranges of stress and temperature, the dissolving of iron carbide and the concurrent precipitation of molybdenum carbide cause strain hardening in these steels. Molybdenum in amounts of 0.5% or less also minimizes temper embrittlement.

Niobium and vanadium are added to improve elevated-strength properties. Vanadium is also added to some of the higher-carbon steels to provide additional resistance to tempering and to retard the growth of carbides at service temperatures. Niobium is sometimes added to these steels to increase their strength through the formation of carbides.

Fatigue Resistance of Steels

FATIGUE is the progressive, localized, and permanent structural change that occurs in a material subjected to repeated or fluctuating strains at nominal stresses that have maximum values less than (and often much less than) the static yield strength of the material. Fatigue may culminate into cracks and cause fracture after a sufficient number of fluctuations. The process of fatigue consists of three stages:

- *Stage I:* initial fatigue damage leading to crack initiation
- *Stage II:* crack propagation to some critical size (a size at which the remaining uncracked cross section of the part becomes too weak to carry the imposed loads)
- *Stage III:* final, sudden fracture of the remaining cross section

Fatigue damage is caused by the simultaneous action of cyclic stress, tensile stress, and plastic strain. If any one of these three is not present, a fatigue crack will not initiate and propagate. The plastic strain resulting from cyclic stress initiates the crack; the tensile stress promotes crack growth (propagation). Careful measurement of strain shows that microscopic plastic strains can be present at low levels of stress where the strain might otherwise appear to be totally elastic. Although compressive stresses will not cause fatigue, compressive loads may result in local tensile stresses.

Fatigue Resistance

Variations in mechanical properties, composition, microstructure, and macrostructure, along with their subsequent effects on fatigue life, have been studied extensively to aid in the appropriate selection of steel to meet specific end-use requirements. Studies have shown that the fatigue strength of steels is usually proportional to hardness and tensile strength; this generalization is not true, however, for high tensile strength values where toughness and critical flaw size may govern ultimate load-carrying ability. Processing, fabrication, heat treatment, surface treatments, finishing, and service environments significantly influence the ultimate behavior of a metal subjected to cyclic stressing.

Predicting the fatigue life of a metal part is complicated because materials are sensitive to small changes in loading conditions and stress concentrations and to other factors. The resistance of a metal structural member to fatigue is also affected by manufacturing procedures such as cold forming, welding, brazing, and plating, and by surface conditions such as surface roughness and residual stresses. Fatigue tests performed on small specimens are not sufficient for precisely establishing the fatigue life of a part. These tests are useful for rating the relative resistance of a material and the baseline properties of the material to cyclic stressing. The baseline properties must be combined with the load history of the part in a design analysis before a component life prediction can be made.

In addition to material properties and loads, the design analysis must take into consideration the type of applied loading (uniaxial, bending, or torsional), loading pattern (either periodic loading at a constant or variable amplitude or random loading), magnitude of peak stresses, overall size of the part, fabrication method, surface roughness, presence of fretting or corroded surface, operating temperature and environment, and occurrence of service-induced imperfections.

Traditionally, fatigue life has been expressed as the total number of stress cycles required for a fatigue crack to initiate and grow large enough to produce catastrophic failure, that is, separation into two pieces. In this article, fatigue data are expressed in terms of total life. For the small samples that are used in the laboratory to determine fatigue properties, this is generally the case; but, for real components, crack initiation may be as little as a few percent or the majority of the total component life.

Fatigue data can also be expressed in terms of crack growth rate. In the past, it was commonly assumed that total fatigue life consisted mainly of crack initiation (stage 1 of fatigue crack development) and that the time required for a minute fatigue crack to grow and produce failure was a minor portion of the total life. However, as better methods of crack detection became available, it was discovered that cracks often developed early in the fatigue life of the material (after as little as 10% of total lifetime) and grow continuously until catastrophic failure occurs. This discovery has led to the use of crack growth rate, critical crack size, and fracture mechanics for the prediction of total life in some applications. The use of fracture mechanics methods to predict fatigue life is discussed in the Section "Failure Analysis" in this Handbook.

Prevention of Fatigue Failure

The incidence of fatigue failure can be considerably reduced by careful attention to design details and manufacturing processes. As long as the metal is sound and free from major flaws, a change in material composition is not as effective in achieving satisfactory fatigue life as are care in design, fabrication, and maintenance during service. The most effective and economical method of improving fatigue strength is improvement in design to: (a) eliminate stress raisers by streamlining the part, (b) avoid sharp surface tears resulting from punching, stamping, shearing, etc., (c) prevent the development of surface discontinuities or decarburization during processing or heat treatment, (d) reduce or eliminate tensile residual stresses caused by manufacturing, heat treating, and welding, and (e) improve the details of fabrication and fastening procedures. Control of or protection against corrosion, erosion, chemical attack, or service-induced nicks and other gouges is an important part of proper maintenance of fatigue strength during active service life.

Symbols and Definitions

Applied Stresses. The mean stress, S_m, is the algebraic average of the maximum and minimum stresses in one cycle, $S_m = (S_{max} + S_{min})/2$. In the completely reversed test, the mean stress is zero. The range of stress, S_r, is the algebraic reference between the maximum and minimum stresses in one cycle, $S_r = S_{max} - S_{min}$. The stress amplitude, S_a, is one-half the range of stress, $S_a = S_r/2 = (S_{max} - S_{min})/2$.

During a fatigue test, the stress cycle is usually maintained constant so that the applied stress conditions can be written as $S_m \pm S_a$, where S_m is the static or mean stress, and S_a is the alternating stress equal to half the stress range. The positive sign is used to denote a tensile stress and the negative sign, a compressive stress. Some of the possible combinations of S_m and S_a are illustrated in Fig. 19. When $S_m = 0$ (Fig. 19a), the minimum tensile stress is equal to the maximum compressive stress; this is called an alternating stress or a completely reversed stress. When $S_m = S_a$ (Fig. 19b), the minimum stress of the cycle is zero; this is called a pulsating or repeated tensile (or compressive) stress. Any other combination is known as a fluctuating stress, which may be a fluctuating tensile stress (Fig. 19c), a fluctuating compressive stress, or a stress that fluctuates between a tensile and a compressive value (Fig. 19d).

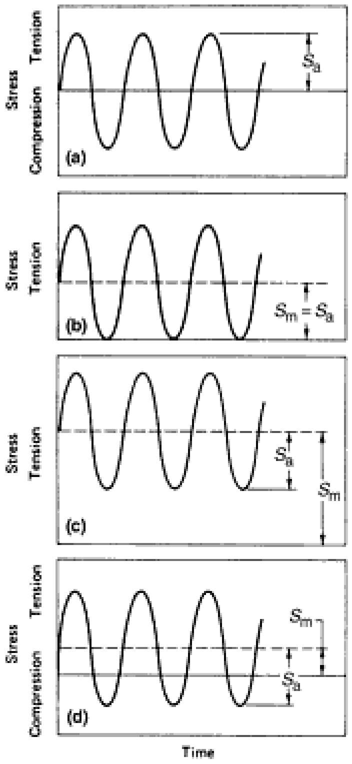


Fig. 19 Types of fatigue test stress. (a) Alternating stress in which $S_m = 0$ and $R = -1$. (b) Pulsating tensile stress in which $S_m = S_a$, the minimum stress is zero, and $R = 0$. (c) Fluctuating tensile strength in which both the minimum and maximum stresses are tensile stresses, $R = \frac{1}{3}$. (d) Fluctuating tensile-to-compressive stress in which the minimum stress is a compressive stress and the maximum stress is a tensile stress, $R = -\frac{1}{3}$

Nominal stresses can be calculated on the net section of a part ($S = P/A$) without consideration of variations in stress conditions caused by holes, grooves, fillets, etc. Nominal stresses are often used in these calculations, although a closer estimate of actual stresses through the use of a stress-concentration factor might be preferred.

Stress ratio is the algebraic ratio of two specified stress values in a stress cycle. Two commonly used stress ratios are the ratio, A, of the alternating stress amplitude to the mean stress ($A = S_a/S_m$) and the ratio, R, of the minimum stress to the maximum stress ($R = S_{min}/S_{max}$). If the stresses are fully reversed, the stress ratio R becomes -1; if the stresses are partially reversed, *R* becomes a negative number less than 1. If the stress is cycled between a maximum stress and no load, the stress ratio *R* becomes zero. If the stress is cycled between two tensile stresses, the stress ratio *R* becomes a positive number less than 1. A stress ratio *R* of 1 indicates no variation in stress, and the test would become a sustained-load creep test rather than a fatigue test.

***S-N* Curves.** The results of fatigue tests are usually plotted as a maximum stress or stress amplitude to number of cycles, *N*, to fracture using a logarithmic scale for the number of cycles. Stress is plotted on either a linear or a logarithmic scale. The resulting curve of data points is called an *S-N* curve. A family of *S-N* curves for a material tested at various stress ratios is shown schematically in Fig. 20. For carbon and low-alloy steels, *S-N* curves typically have a fairly straight slanting portion at low cycles changing into a straight, horizontal line at higher cycles, with a sharp transition between the two.

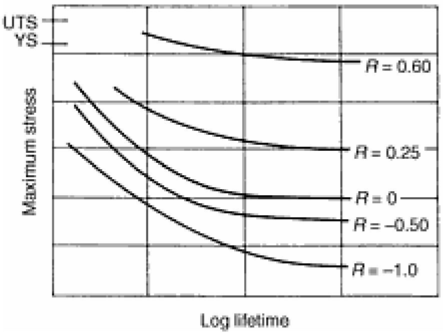


Fig. 20 Schematic *S-N* curves for a material at various stress ratios. UTS and YS indicate ultimate tensile strength and yield strength, respectively, in uniaxial tensile testing.

An *S-N* curve usually represents the median life for a given stress--the life that half the specimens attain or surpass and half fail to attain. Scatter of fatigue lives can cover a very wide range.

Fatigue limit (or endurance limit) is the value of the stress below which a material can presumably endure an infinite number of stress cycles--that is, the stress at which the *S-N* diagram becomes and appears to remain horizontal. The existence of a fatigue limit is typical for carbon and low-alloy steels.

Fatigue strength, which should not be confused with fatigue limit, is the stress to which the material can be subjected for a specified number of cycles. Fatigue strength is used for materials, such as most nonferrous metals, that do not exhibit well-defined fatigue limits. It is also used to describe the fatigue behavior of carbon and low-alloy steels at stresses higher than the fatigue limit.

Stress-Concentration Factor. Concentrated stress in a metal is evidenced by discontinuities such as notches, holes, and scratches, and by changes in microstructure. The stress-concentration factor, K_t, is the ratio of the greatest stress in the region of the notch (or other stress concentrators) to the corresponding nominal stress. For determination of K_t, the greatest stress in the region of the notch is calculated from the theory of elasticity, or equivalent values may be derived experimentally. An experimental stress-concentration factor is a ratio of stress in a notched specimen to the stress in a smooth (unnotched) specimen.

Fatigue notch factor, K_f, is the ratio of the fatigue strength of a smooth (unnotched) specimen to the fatigue strength of a notched specimen at the same number of cycles. The fatigue notch factor will vary with the position on the *S-N* curve and with the mean shear stress. At high stress levels and short cycles, the factor is usually less than at lower stress levels and longer cycles due to blunting of the notch by plastic deformation.

Fatigue notch sensitivity, q, is determined by comparing the fatigue notch factor, K_f, and the stress-concentration factor, K_t, for a specimen of a given size containing a stress concentrator of a given shape and size. A common definition of fatigue notch sensitivity is $q = (K_f - 1)/(K_t - 1)$, in which q may vary between zero (where $K_f = 1$) and 1 (where $K_f = K_t$). This value may be stated as a percentage. As the fatigue notch factor varies with the position on the *S-N* curve, so will the notch sensitivity. Most metals are fully notch sensitive at low stresses and long cycles. If they are not, it may be that the fatigue strengths for the smooth (unnotched) specimens are lower than they could be because of surface imperfections.

Stress-Based Approach to Fatigue

The design of a machine element that will be subjected to cyclic loading can be approached by adjusting the configuration of the part so that the calculated stresses fall safely below the required line on an *S-N* plot. In a stress-based analysis, the material is assumed to deform in a nominally elastic manner, and local plastic strains are neglected. To the extent that these approximations are valid, the stress-based approach is useful. These assumptions imply that all the stresses will essentially be elastic. The stress-based approach is best applied to components that look like the test samples and are approximately the same size. Much of the technology in application of this approach is based on steels. Other materials may not respond in a similar manner.

Examples of the stress-fatigue life approach are given in Fig. 21 and 22. Figure 21 shows the combinations of cyclic stresses that can be tolerated by the same steel when the specimens are heat treated to different tensile strengths ranging from 860 to 1790 MPa (125 to 260 ksi). The effect of elevated temperature on the fatigue behavior of 4340 steel heat treated to 1035 MPa (150 ksi) is shown in Fig. 22. An increase in temperature reduces the fatigue strength of the steel and is most deleterious for those applications in which the stress ratio, *R*, lies between 0.4 and 1.0. A decrease in temperature may increase the fatigue limit of steel; however, parts with preexisting cracks may also show decreased total life as temperature is lowered. because of accompanying reductions in critical crack size and fracture toughness.

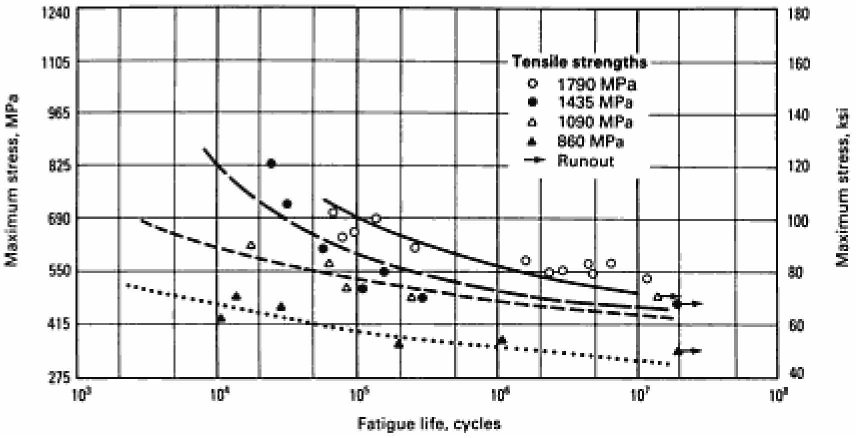


Fig. 21 Room temperature *S-N* curves for AISI 4340 alloy steel with various ultimate tensile strengths and with *R* = -1.0

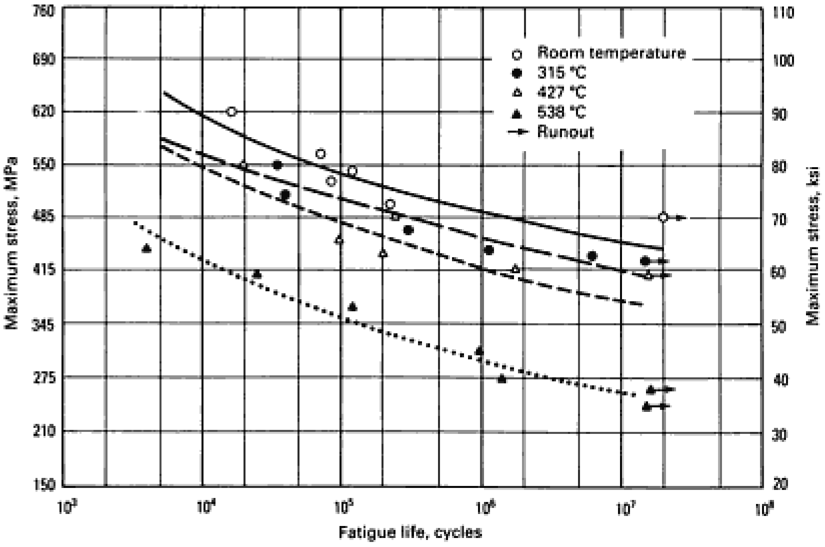


Fig. 22 ***S-N*** **curves at various temperatures for AISI 4340 alloy steel with an ultimate tensile strength of 1090 MPa (158 ksi). Stress ratio,** ***R,*** **equals -1.0**

Strain-Based Approach to Fatigue

A strain-based approach to fatigue, developed for the analysis of low-cycle fatigue data, has proved to be useful for analyzing long-life fatigue data as well. The approach can take into account both elastic and plastic responses to applied loadings. The data are presented on a log-log plot similar in shape to an *S-N* curve; the value plotted on the abscissa is the number of strain reversals (twice the number of cycles) to failure, and the ordinate is the strain amplitude (half the strain range).

During cyclic loading, the stress-strain relationship can usually be described by a loop, such as that shown in Fig. 23. For purely elastic loading, the loop becomes a straight line whose slope is the elastic modulus, *E*, of the material. The occurrence of a hysteresis loop is most common. The definitions of the plastic strain range, $\Delta\varepsilon_p$, the total strain range, $\Delta\varepsilon_t$, and the stress range, $\Delta\sigma$, are indicated in Fig. 23. A series of fatigue tests, each having a different total strain range, will generate a series of hysteresis loops. For each set of conditions, a characteristic number of strain reversals is necessary to cause failure.

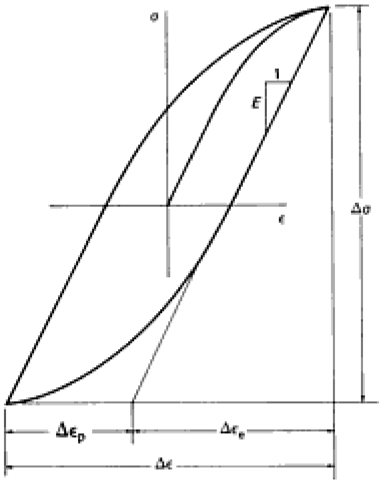


Fig. 23 Stress-strain hysteresis loop

As shown in Fig. 24, a plot on logarithmic coordinates of the plastic portion of the strain amplitude (half the plastic strain range) versus the fatigue life often yields a straight line, described by the equation:

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f(2N_f)^c$$

where ε_f is the fatigue ductility coefficient, c is the fatigue ductility exponent, and N_f is the number of cycles to failure.

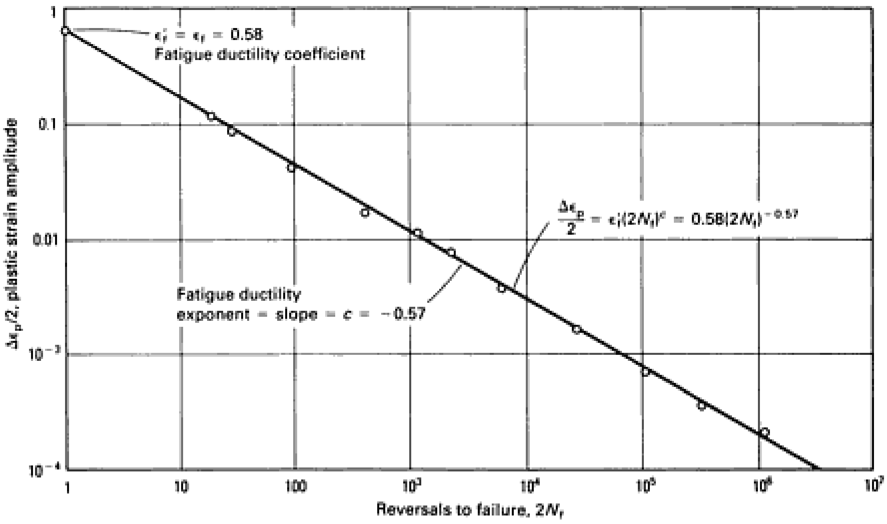


Fig. 24 Ductility versus fatigue life for annealed AISI-SAE 4340 steel

Effect of Metallurgical Variables on Fatigue Behavior

The metallurgical variables having the most pronounced effects on the fatigue behavior of carbon and low-alloy steels are strength level, ductility, cleanliness of the steel, surface conditions, and aggressive environments. At least partly because of the characteristic scatter of fatigue testing data, it is difficult to distinguish the direct effects of other variables such as composition on fatigue from their effects on the strength level of steel.

Strength Level. For most steels with hardnesses below 400 HB (not including precipitation-hardening steels), the fatigue limit is about half the ultimate tensile strength. Thus, any heat treatment or alloying addition that increases the strength (or hardness) of a steel can be expected to increase its fatigue limit as shown in Fig. 21 for a low-alloy steel (AISI 4340). However, as shown in Fig. 25 for medium-carbon steel, a higher hardness (or strength) may not be associated with improved fatigue behavior in a low-cycle regime ($<10^3$ cycles) because ductility may be a more important factor.

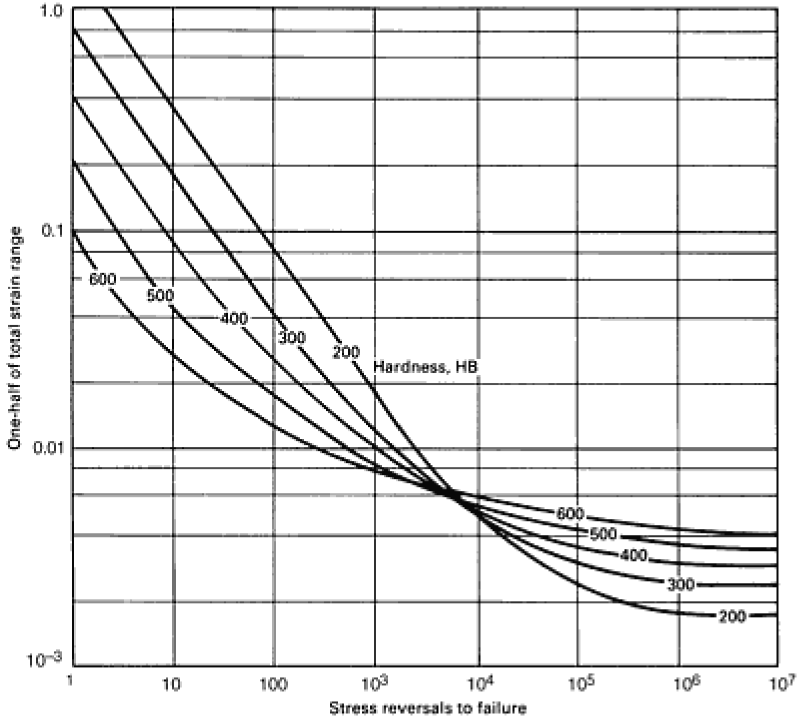


Fig. 25 Effect of hardness level on plot of total strain versus fatigue life. These are predicted plots for typical medium-carbon steel at the indicated hardness levels.

Ductility is generally important to fatigue life only under low-cycle fatigue conditions. Exceptions to this include spectrum loading where there is an occasional overload with millions of smaller cycles, or extremely brittle materials where crack propagation dominates.

Cleanliness of a steel refers to relative freedom from nonmetallic inclusions. These inclusions generally have a deleterious effect on the fatigue behavior of steels (Fig. 26), particularly for long-life applications. The type, number, size, and distribution of nonmetallic inclusions can have a greater effect on the fatigue life of carbon and alloy steel than will differences in composition, microstructure, or stress gradients. Nonmetallic inclusions, however, are rarely the prime cause of the fatigue failure of production parts; if the design fatigue properties were determined using specimens containing inclusions representative of those in the parts, any effects of these inclusions would already be incorporated in the test results.

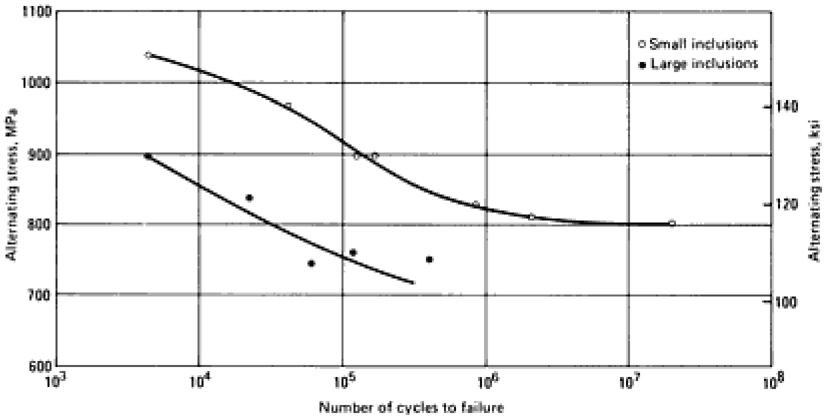


Fig. 26 Effect of nonmetallic inclusion size on fatigue. Steels were two lots of AISI-SAE 4340H: one lot (lower curve) contained abnormally large inclusions; the other lot (upper curve) contained small inclusions.

Large nonmetallic inclusions can often be detected by nondestructive inspection; steels can be selected on the basis of such inspection. Vacuum melting, which reduces the number and size of nonmetallic inclusions, increases the fatigue limit of 4340 steel, as can be seen in Table 5. Improvement in fatigue limit is especially evident in the transverse direction.

Table 5 Influence of steelmaking practices on fatigue limit of SAE 4340 steel

	Electric furnace-melted	Vacuum-melted
Longitudinal fatigue limit, MPa (ksi)	800 (116)	**960 (139)**
Transverse fatigue limit, MPa (ksi)	545 (79)	**825 (120)**
Ratio transverse to longitudinal	0.68	**0.86**
Hardness, HRC	**27**	**29**

Determined in repeated-bending fatigue test ($R = 0$).

Surface conditions of a metal part can significantly affect the resistance to fatigue. Surface imperfections and roughness reduce the fatigue limit of the part; this effect is most apparent for high-strength steels. Residual stresses also play a key role. Tensile residual stresses at the surface, such as those produced by rough grinding, reduce fatigue life (top of Fig. 27). Compressive residual stresses at the surface, such as those produced by shot peening, can improve fatigue resistance (bottom portion of Fig. 27).

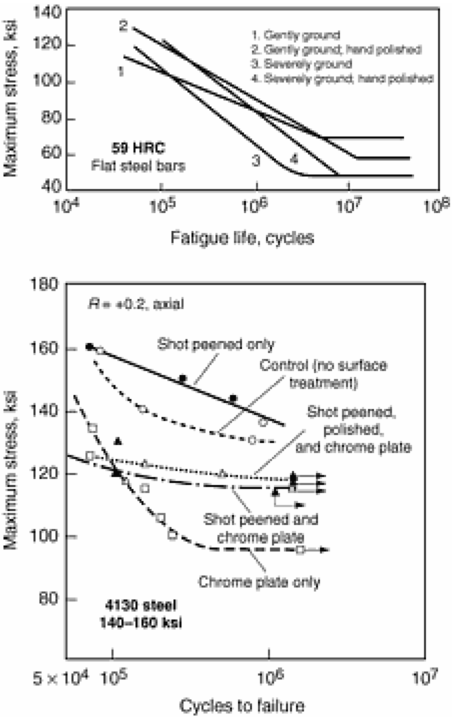


Fig. 27 Influence of surface roughness and finish on fatigue resistance of smooth specimens. Roughness and finish effects include some residual stress effects, as noted in test. Some surface treatments, such as hard chrome plating, can produce surface cracks, which result in a lower life.

Decarburization is the removal of carbon from the surface of a steel part; as indicated in Fig. 28, it significantly reduces the fatigue limit of steel. Decarburization of from 0.08 to 0.75 mm (0.003 to 0.030 in.) on AISI-SAE 4340 notched specimens heat treated to a strength level of 1860 MPa (270 ksi) reduces the fatigue limit almost as much as a notch with $K_t = 3$.

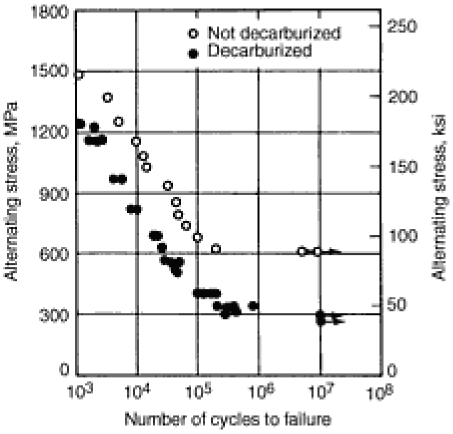


Fig. 28 Effect of decarburization on the fatigue behavior of a steel

When subjected to the same heat treatment as the core of the part, the decarburized surface layer is weaker and therefore less resistant to fatigue than the core. Hardening a part with a decarburized surface can also introduce residual tensile stresses, which reduce the fatigue limit of the material. Results of research studies have indicated that fatigue properties lost through decarburization can be at least partially regained by recarburization (carbon restoration in the surfaces) or by shot peening.

Embrittlement of Steels

STEELS are susceptible to a number of embrittlement (loss of ductility) phenomena. Some of these affect a wide range of compositions, while others are specific to a rather narrow range of compositions. These problems promote brittle service failures that can be catastrophic or can reduce the service life of a component. This article reviews the embrittlement problems encountered during thermal treatment or elevated-temperature service. The forms of embrittlement associated with carbon and low-alloy steels that will be discussed include:

- Strain-age embrittlement (low-carbon steels)
- Blue brittleness (carbon steels)
- Quench-age embrittlement (low-carbon steels)
- Temper embrittlement (alloy steels)
- Tempered martensite embrittlement (ultrahigh-strength alloy steels)
- Graphitization (carbon steels and chromium-molybdenum alloy steels)
- Overheating (carbon and alloy steels)
- Quench cracking (medium-carbon alloy steels)

More highly alloyed steels are also susceptible to embrittlement phenomena. The types of embrittlement affecting stainless steels and maraging steels include:

- Sensitization (austenitic and duplex stainless steels)
- 475 °C, or 885 °F, embrittlement (ferritic stainless steels)
- Sigma-phase embrittlement (austenitic, ferritic, and duplex stainless steels)
- Thermal embrittlement (maraging steels)

Only the thermal embrittlement of maraging steels will be discussed in this article. Embrittlement mechanisms associated with stainless steels are described in the Section "Stainless Steels" in this Handbook.

In addition, steels (and other metals and alloys) can be embrittled by environmental conditions. The forms of environmental embrittlement include:

- Neutron embrittlement
- Hydrogen embrittlement
- Stress-corrosion cracking
- Liquid-metal and solid-metal embrittlement

These forms of embrittlement are described elsewhere in this Handbook (see, for example, the Section "Failure Analysis").

Strain-Age Embrittlement

Strain aging occurs in low-carbon steels that are deformed certain amounts and then aged, which produces an increase in strength and hardness but a loss in ductility. The degree of deformation, or cold work, is important. Generally, about a 15% reduction in thickness provides the maximum effect. The resulting brittleness varies with the aging temperature and time. Aging at room temperature is very slow, requiring several months to obtain maximum embrittlement. As the aging temperature is increased, the time for maximum embrittlement decreases, with embrittlement occurring in a matter of minutes at about 200 °C (400 °F).

Strain aging may also lead to Lüders bands (stretcher-strain marks) on cold-formed low-carbon sheet components. These marks are cosmetic defects rather than cracks, but their presence on formed parts is unacceptable. During tensile loading, sheet steel that is susceptible to this defect exhibits nonuniform yielding followed by uniform elongation. The elongation at maximum load and the total elongation are reduced, decreasing cold formability. In a non-aluminum-killed sheet steel, a small amount of deformation, typically 1% reduction, suppresses the yield point for several months. This process is referred to as roller leveling or temper rolling. This process is more effective in eliminating the sharp yield point and preventing strain aging than stretching the steel through the Lüders strain, which requires about 4 to 6% reduction. However, if the material is not formed within the safe period, discontinuous yielding eventually returns and impairs formability.

Certain coating treatments, such as hot-dip galvanizing, can produce a high degree of embrittlement in areas that were cold worked the critical amount; this can lead to brittle fractures. To prevent this problem, the part can be annealed before it is galvanized.

Blue Brittleness

Carbon steels generally exhibit an increase in strength and a reduction of ductility and toughness at temperatures around 300 °C (570 °F). Because such temperatures produce a bluish temper color on the surface of the specimen, this problem has been called blue brittleness. It is generally believed that blue brittleness is an accelerated form of strain-age embrittlement. Deformation in the blue-heat range, followed by testing at room temperature, produces an increase in strength that is greater than when the deformation is performed at ambient temperature. Blue brittleness can be eliminated if elements that tie up nitrogen, such as aluminum or titanium, are added to the steel (studies have shown that higher nitrogen contents lead to both blue brittleness and strain-age embrittlement).

Quench-Age Embrittlement

If low-carbon steels are rapidly cooled from temperatures slightly below the lower critical temperature (Ac_1) of the steel, the hardness of the steel increases, with a resultant loss of ductility upon aging at room temperature. As with strain-aging, quench-age embrittlement is a function of time at the aging temperature until the maximum degree of embrittlement is reached. An aging period of several weeks at room temperature is required for maximum embrittlement.

A decrease in the quenching temperature decreases the extent of the embrittlement. Quenching from temperatures of 560 °C (1040 °F) and below does not produce quench-age embrittlement. Steels with carbon contents of 0.04 to 0.12% appear most susceptible to quench-age embrittlement; increasing the carbon content above 0.12% reduces the effect. Quench-age embrittlement results from (a) precipitation of solute carbon at existing dislocations and (b) precipitation hardening because of differences in the solid solubility of carbon in ferrite at different temperatures.

Temper Embrittlement

Temper embrittlement (also known as temper brittleness, two-step temper embrittlement, or reversible temper embrittlement) is associated with tempered alloy steels that are heated within, or slowly cooled through, a critical temperature range, generally 300 to 600 °C (570 to 1110 °F) for low-alloy steels. This treatment causes a decrease in toughness as determined with Charpy V-notch impact specimens. It is a particular problem for heavy-section components, such as pressure vessels and turbine rotors, that are slowly cooled through the embrittling range after tempering and also experience service at temperatures within the critical range.

Temper embrittled steels exhibit an increase in their ductile-to-brittle transition temperature (DBTT) and a change in fracture mode in the brittle test temperature range from cleavage to intergranular. The DBTT can be assessed in several ways. The most common is the temperature for 50% ductile and 50% brittle fracture (50% fracture appearance transition temperature, or FATT), or the lowest temperature at which the fracture is 100% ductile (100% fibrous criterion). Transition temperatures based on absorbed energy values are not normally employed. Temper embrittlement is reversible;

that is, the toughness of embrittled steels can be restored by tempering them above the critical region, followed by rapid cooling (e.g., water quenching). This decreases the DBTT and changes the low-temperature (that is, below the 50% FATT) intergranular brittle appearance back to the cleavage mode.

Temper embrittlement occurs only in alloy steels, not in plain carbon steels, and the degree of embrittlement varies with alloy steel composition. Therefore, the alloying elements present, and their combinations and levels, are important. Both bulk composition and impurity levels are important, although without the latter, temper will not occur. The most potent impurity elements are antimony, phosphorus, tin, and arsenic (in order of decreasing potency). Manganese and silicon also promote embrittlement. Alloys containing nickel and chromium in combination are more susceptible than those that contain nickel or chromium separately. Molybdenum additions are effective in retarding or eliminating temper embrittlement when impurities are present. However, to be effective, the molybdenum must be dissolved in the ferritic matrix, not tied up as carbides.

Tempered Martensite Embrittlement

Tempered martensite embrittlement (TME, also known as one-step temper embrittlement and as 350 °C, or 500 °F, embrittlement) of high-strength alloy steels occurs upon tempering in the range of 205 to 370 °C (400 to 700 °F). It differs from temper embrittlement in the strength of the material and the temperature exposure range. In temper embrittlement, the steel is usually tempered at a relatively high temperature, producing lower strength and hardness, and embrittlement occurs upon slow cooling after tempering and during service at temperatures within the embrittlement range. In TME, the steel is tempered within the embrittlement range, and service exposure is usually at room temperature. This is why temper embrittlement is often called two-step temper embrittlement, while TME is often called one-step temper embrittlement.

It is well established that lower bainite is also embrittled when tempered in the range of 205 to 370 °C (400 to 700 °F). Other structures, such as upper bainite and pearlite/ferrite, are not embrittled by tempering in this region.

While temper embrittlement is evaluated by the change in the DBTT, most studies of TME have evaluated only the change in room-temperature impact energy. In general, when an as-quenched alloy steel is tempered, the toughness at room temperature increases with tempering temperature, up to about 200 °C (390 °F). With further increases in tempering temperature, the toughness decreases. Then, with increasing tempering temperatures above about 400 °C (750 °F), the toughness increases again. This change in toughness with tempering temperature is not apparent when examining hardness or tensile strength data, which generally decrease with increasing tempering temperatures.

The cause of TME is not as well defined as the cause of temper embrittlement. 500 °F embrittlement is believed to be caused by ferrite networks resulting from precipitation of cementite platelets along prior austenite grain boundaries. However, some investigators believe that the precipitation of grain-boundary cementite platelets as such is responsible for TME.

Steels containing substantial amounts of chromium or manganese are highly susceptible to TME. Aluminum contents above 0.04% reduce embrittlement, and additions of 0.1% aluminum usually eliminate the problem. Some degree of embrittlement has been observed when phosphorus, antimony, arsenic, tin, silicon, manganese, or nitrogen additions were made to high-purity steels. Additions of nitrogen produced intergranular fractures, but the other embrittling agents did not. (Commercial grades of steel that are subjected to TME treatments fracture intergranularly.)

Embrittlement in low-alloy steels heat treated to high strength levels can be minimized by:

- Developing special steels with retarded martensite-tempering characteristics
- Developing steels with faster rates of martensite tempering
- Using steels capable of transformation to 100% upper bainite at the desired strength level and section size
- Avoiding tempering in the region of susceptibility
- Using the lowest possible carbon content consistent with the desired strength level

Graphitization

Graphitization of carbon and carbon-molybdenum steel piping during service at elevated temperatures above 425 °C (800 °F) has caused numerous failures in steam power plants and refineries. Graphite formation generally occurs in a narrow region in the heat-affected zone of a weld where the metal has been briefly heated above the lower critical temperature. The graphitization tendency of carbon and carbon-molybdenum steels is increased when the aluminum content exceeds about 0.025%. Steels deoxidized with silicon may also be susceptible to graphitization. Deoxidation with titanium usually will produce good resistance to graphitization. Carbon-molybdenum steels exhibit greater resistance to graphitization than do carbon steels.

The degree of embrittlement depends on the distribution, size, and shape of the graphite. The severity of graphitization is frequently evaluated by bend testing. If graphitization is detected in its early stages, the material often can be rehabilitated by normalizing and tempering just below the lower critical temperature. Steel that has undergone more severe graphitization cannot be salvaged in this manner; the defective region must be cut out and rewelded, or the section must be replaced. Carbon and carbon-molybdenum steels can be rendered less susceptible to graphitization by tempering just below the lower critical temperature.

Overheating

The overheating of steels occurs when they are heated to excessively high temperatures prior to hot working. Heating at even higher temperatures causes incipient grain-boundary melting, a problem known as burning. Thus, overheating occurs in the temperature range between the safe range normally used prior to hot working and the higher range where liquation begins. Hot working after burning generally results in the tearing or rupture of the steel due to the liquid in the grain boundaries. Hot working after overheating generally does not result in cracking; if sufficient hot reduction occurs, the influence of overheating may be minor or negligible. If the degree of hot reduction is small, mechanical properties, chiefly toughness and ductility, will be affected.

Fracture surfaces of overheated steels that are given limited hot reduction often exhibit a coarse-grain faceted appearance. Such features are most evident after quenching and tempering to develop optimum toughness.

Although the mechanical properties of burnt steels are always very poor, the mechanical properties of overheated steels show considerable scatter. For tensile tests, the elongation and reduction of area are most affected by overheating and decrease with increasing heating temperature. Fracture faceting and substantial decreases in tensile ductility normally are observed after severe overheating.

Impact properties are usually more sensitive to overheating than tensile ductility. In examining impact test results, several interrelated features should be examined: change in upper-shelf energy, impact strength transition temperature, and the presence of facets.

Quench Cracking

The production of fully martensitic microstructures in steels requires a heat treatment cycle that involves quenching after austenitization. The composition of the steel, its size, and the desired depth of hardening dictate the required quench medium. Certain steels are known to be susceptible to cracking during or slightly after quenching. This is a relatively common problem for tool steels, particularly those that require liquid quenching.

Numerous factors can contribute to cracking susceptibility:

- Carbon content
- Hardenability
- M_s temperature (the temperature at which martensite starts to form)
- Part design
- Surface quality
- Furnace atmosphere
- Heat treatment practice

As the carbon content is raised, the M_s and the M_f (the temperature at which martensite formation ends) decrease, and the volumetric expansion and transformation stresses accompanying martensite formation increase. In general, steels with less than 0.35% C are free of quench cracking problems. Such low-carbon steels have higher M_s and M_f temperatures that allow some stress relief to occur during the quench. Also, transformation stresses are lower, and the lower strength of the martensite formed (low-carbon lath martensite) can accommodate the strains more readily than a higher-carbon steel.

Alloy steels with ideal critical diameters of 4 or greater are more susceptible to quench cracking than lower-hardenability steels. Quench crack sensitivity also increases as the severity of the quench rate increases. Control of the austenitizing temperature is also important, particularly for high-carbon tool steels. Excessive retained austenite and coarse-grain structures promote quench cracking. Quench uniformity is important, particularly when liquid quenchants are employed. When high-carbon steels are quenched to form martensite, they are in a highly stressed condition. Therefore, tempering must be done immediately after quenching to relieve these stresses and minimize the risk of cracking. Surface quality is also very important because seams, laps, tool marks, stamp marks, and so on act as stress concentrators to locate and enhance quench cracking susceptibility.

Thermal Embrittlement of Maraging Steels

Maraging steels fracture intergranularly at low impact energies if improperly processed after hot working. This problem, known as thermal embrittlement, occurs when maraging steels that have been heated above 1095 °C (2000 °F) are slowly cooled through, or held within, the temperature range of 980 to 815 °C (1800 to 1500 °F). The embrittlement is caused by the precipitation of TiC and/or Ti(C,N) on the austenite grain boundaries during cooling through, or holding within, the critical temperature range. The degree of embrittlement increases with time within the critical range. Increased levels of carbon and nitrogen render maraging steels more susceptible to thermal embrittlement. Auger analysis has shown that embrittlement begins with the diffusion of titanium, carbon, and nitrogen to the grain boundaries, and the appearance of TiC or Ti(C,N) precipitates represent an advanced stage of embrittlement.

Notch Toughness of Steels

TOUGHNESS is an indication of the capacity of a steel to absorb energy and is dependent on strength as well as ductility. Notch toughness is an indication of the capacity of a steel to absorb energy when a stress concentrator or notch is present. All carbon and low-alloy steels undergo a ductile-to-brittle transition as the temperature is lowered. Depending on chemical composition, product processing, and service environment, this transition can occur at temperatures from several hundred degrees above to several hundred degrees below room temperature. A number of notch impact tests have been developed to screen and rate steel product toughness on a relative basis and to determine the ductile-to-brittle transition for a specific steel product. Examples of various notch toughness tests are:

Test	ASTM specification
Charpy V-notch	**E 23**
Izod cantilever-beam	**E 23**
Drop-weight nil-ductility	**E 208**
Drop-weight tear	**E 436**
Dynamic tear	**E 604**

Of all the notched tests, the most widely applied is the Charpy V-notch test.

An illustration of a Charpy testing machine is shown in Fig. 29. The Charpy specimen shown in Fig. 30 is generally oriented so that the root of the notch lies perpendicular to the surface of the component being tested. The orientation (longitudinal or transverse) of the specimen is selected according to the appropriate product specification. The specimen is held for 10 min at the test temperature and then broken in the Charpy-type impact tester by a single blow of a freely swinging pendulum. Upon the breaking of the Charpy specimen, three criteria are commonly measured. The loss of energy in the pendulum swing provides the energy in terms of joules (foot-pounds of force) absorbed in breaking the specimen. The fracture appearance of the broken specimen can be rated in terms of ductile and brittle fracture modes. Also, the lateral expansion at the base of the fracture opposite the notch can be measured. Any of these three criteria can be plotted versus temperature to obtain a ductile-to-brittle transition curve. The most commonly used measurement is energy absorbed. For steel product specifications, a specific Charpy V-notch requirement can be negotiated between the customer and supplier (for example, a minimum energy absorbed at a specified test temperature).

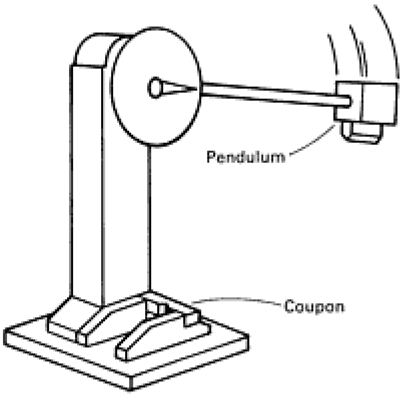


Fig. 29 Typical Charpy testing machine. The coupon is chilled to the desired temperature, then quickly placed into the anvil to be broken.

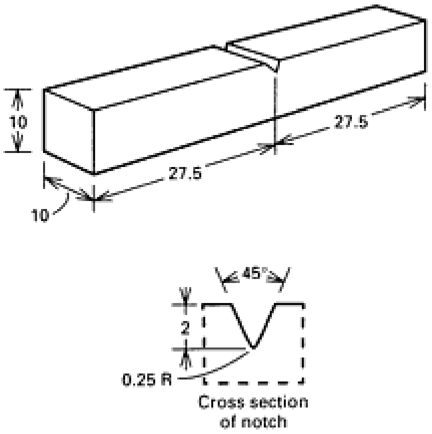


Fig. 30 Charpy V-notch specimen used for the evaluation of notch toughness (ASTM E 23). Dimensions given in millimeters

Ductile-to-Brittle Transition

In body-centered cubic metals such as plain carbon and low-alloy steels, a unique characteristic is found during impact testing over a temperature range of approximately 120 to -130 °C (250 to -200 °F). This characteristic is a ductile-to-brittle transition in toughness. At the higher end of the temperature range, the fracture behavior is ductile with an accompanying large degree of plastic deformation. The ductile mode of fracture is most commonly associated with microvoid coalescence. At the lower end of the range the fracture is brittle, and the mode of fracture is cleavage with little or no plastic deformation. Figure 31 is a Charpy curve showing a typical ductile-to-brittle transition in steel. The plot shows absorbed energy versus test temperature. The stable region at the higher temperatures is called the upper shelf, and the stable region at the lower temperatures is called the lower shelf. The region between the upper and lower shelves that displays a mixture of ductile and cleavage fracture is called the transition region.

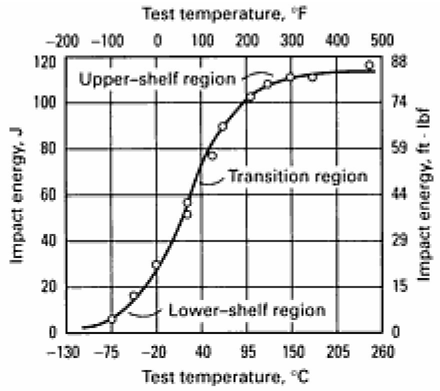


Fig. 31 Charpy curve of impact energy versus test temperature for a Ni-Cr-Mo steel

Figure 32(a) shows an example of the fracture surface of a broken Charpy specimen from a low-alloy steel tested at the upper-shelf region. The absorbed energy was 117 J (86 ft · lbf). The fracture appears as a ductile, dimplelike surface with many shear lips. Inclusions, in this case titanium nitrides (square particles) and manganese sulfides (round particles), are usually located at the center of each large dimple. These inclusions initiated the formation of a void, which created the dimple. Figure 32(b) shows the typical cleavage fracture surface at the lower-shelf region for the same steel. The absorbed energy was 6.1 J (4.5 ft · lbf). In fractograph, no regions of ductile tearing or shear lips are present.

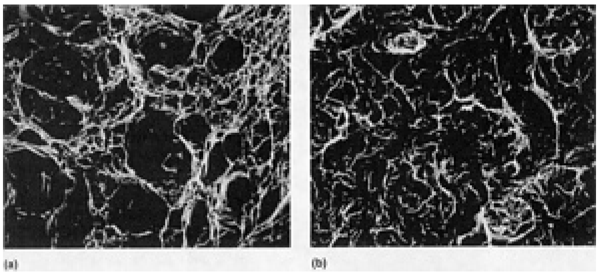


Fig. 32 SEM micrographs showing the fracture surfaces of broken Charpy V-notch specimens (Ni-Cr-Mo steel) tested in the (a) upper-shelf region and (b) lower-shelf region of the Charpy curve shown in Fig. 31. Both 670×

From the Charpy curve shown in Fig. 31, a transition temperature can be determined. There are a number of criteria for transition temperature, one being the median temperature of this transition range. In Fig. 31 this would be 25 °C (75 °F). The transition temperature could also be the temperature at a specified absorbed energy (20 J or 15 ft · lbf, for example). Thus, in Fig. 31, the 20 J (15 ft · lbf) transition temperature would be -30 °C (-25 °F).

In addition to absorbed energy, other important measurements can be obtained from the Charpy test. For example, the lateral expansion can be measured on the broken Charpy specimen at the edge of the specimen opposite to the notch. Lateral expansion is used as a measure of notch toughness similar to absorbed energy. Another important measurement is fracture appearance transition temperature (FATT). To obtain this value, the percentage of shear (fibrous fracture) in the fracture surface is measured. The 50% FATT represents the temperature at 50% shear (50% fibrous). The 100% FATT would represent the temperature at 100% shear. Figure 33 shows a plot of percent shear versus test temperature for the same steel as in Fig. 31. From Fig. 33 the 50% FATT is 25 °C (75 °F). Note that this is the same temperature as determined from the data plotted in Fig. 31. In some steels the energy-established transition temperature and FATT may not be the same. In some steels it may be difficult to measure percent shear because of woody fracture surfaces caused by stringer-type inclusions, and so on. For these cases, it would be more appropriate to use the lateral expansion and absorbed-energy measurements to obtain a more accurate transition temperature.

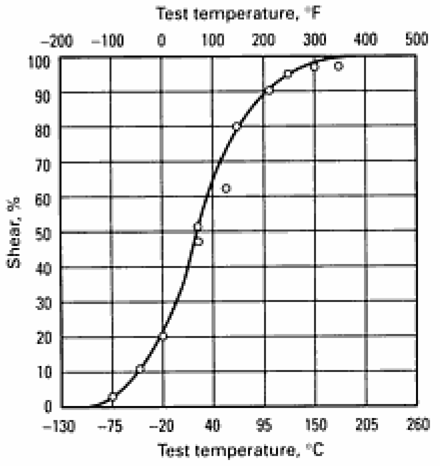


Fig. 33 Charpy curve of percent shear versus test temperature for the same Ni-Cr-Mo steel in Fig. 31

Selection of the most appropriate method of measuring transition temperature for a given application is difficult and requires an understanding of both toughness testing and service behavior. Often, additional tests are needed to establish a correlation between the transition temperature determined using a certain method and the service behavior of a specific structure made of the same material.

Effects of Composition

The composition of a steel, as well as its microstructure and processing history, significantly affects both the ductile-to-brittle transition temperature range and the energy absorbed during fracture at any particular temperature. The effect of the various alloying elements and those of microstructural and processing variables are intimately interrelated; in practice, it is difficult to change one variable without affecting another. Each individual alloying element contributes to notch toughness to varying degrees.

Carbon. Increasing carbon content increases transition temperature and decreases upper-shelf fracture energy primarily as a result of increased strength and hardness. These effects, measured by Charpy V-notch impact tests, are shown in Fig. 34. Carbon is one of the most potent alloying elements in its effect on notch toughness and strength. Consequently, for maximum toughness, the carbon content should be kept as low as possible, consistent with strength requirements. Low-carbon steels tend to have very steep transition curves.

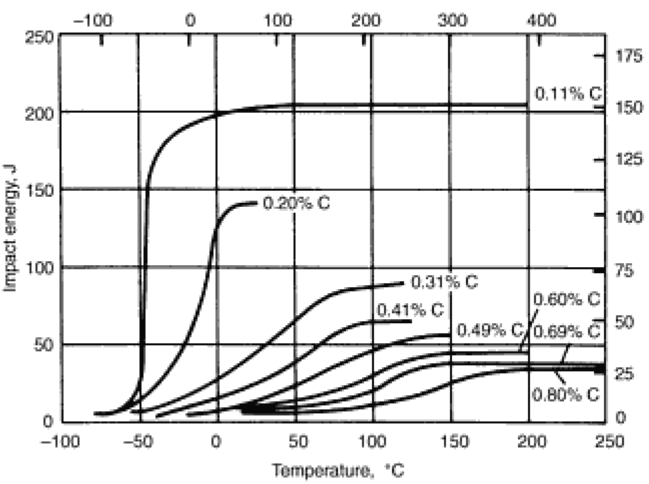


Fig. 34 Variation in Charpy V-notch impact energy with temperature for normalized plain carbon steels of

various carbon contents

Manganese has a variety of effects on transition temperature. In low-carbon steels, it can substantially reduce the transition temperature, as shown in Fig. 35. In higher-carbon steels, manganese may be less beneficial. In a hardened and tempered steel, manganese can have the opposite effect, as illustrated in Fig. 36. Manganese can make the steel susceptible to temper embrittlement, and it may cause the formation of less tough upper bainite (rather than fine pearlite) during normalizing.

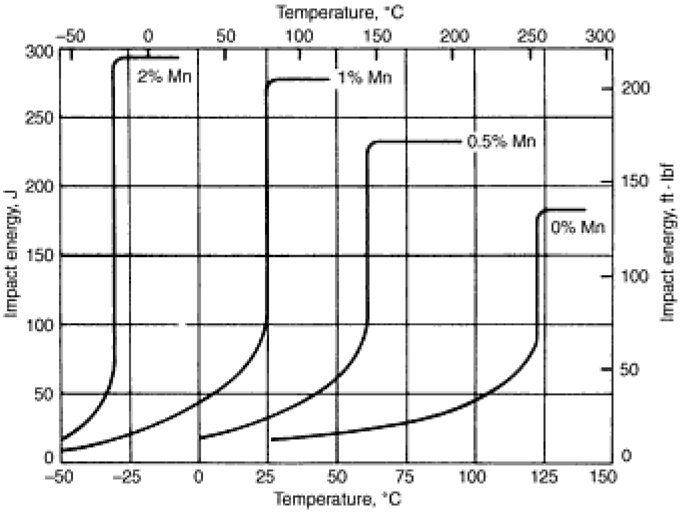


Fig. 35 Variation in Charpy V-notch impact energy with temperature for furnace-cooled Fe-Mn-0.05C alloys containing various amounts of manganese

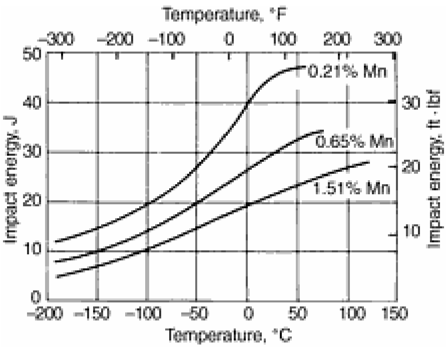


Fig. 36 Variation in Charpy V-notch impact energy with temperature for alloy steels containing 0.35% C, 0.35% Si, 0.80% Cr, 3.00% Ni, 0.30% Mo, 0.10% V and the indicated amounts of manganese. The steels were hardened and tempered to a yield strength of approximately 1175 MPa (170 ksi). The microstructures of these steels contained tempered martensite.

Sulfur. The effect of sulfur on the notch toughness of steels is directly related to deoxidation practice. For rimmed, semi-killed, and silicon-killed steels, sulfur in amounts up to about 0.04% has a negligible effect on notch toughness. However, for silicon-aluminum-killed steels, a reduction in sulfur content can substantially increase upper-shelf energy.

Phosphorus has a strongly deleterious effect on the notch toughness of steel. It raises the 50% FATT about 7 °C (13 °F) for each 0.01% P and reduces upper-shelf energy. In addition, phosphorus increases the susceptibility of some steels to temper embrittlement.

Silicon, used in amounts of 0.15 to 0.30% to deoxidize steels, generally lowers the ductile-to-brittle fracture transition and raises upper-shelf energy. Compared to rimmed or semikilled steels, silicon-killed steels are cleaner and have more uniform ferrite grains. These effects are probably caused by variations in steelmaking practice characteristic of the deoxidation methods used, rather than by the silicon content.

Nitrogen, by itself, lowers the upper-shelf energy and raises the transition temperature. However, most nitrogenized steels are deoxidized with silicon and aluminum, both of which combine with nitrogen. Aluminum nitrides formed during deoxidation serve to stabilize grain size and thus improve the notch toughness of these steels.

Nickel is useful for improving the notch toughness of steels at low temperatures. Ferritic steels with high nickel content ($2\frac{1}{4}$ to 9% Ni) are used for applications involving exposure to temperatures from 0 to -195 °C (32 to -320 °F). Nickel is less effective in improving the toughness of medium-carbon steels than low-carbon steels. Some high-nickel alloy steels, such as maraging steels and austenitic stainless steels, do not exhibit the typical ductile-to-brittle transition (austenitic steels, being face-centered cubic, do not have a ductile-to-brittle transition). The high nickel content reduces upper-shelf fracture energy--but to a level that is still quite acceptable for most applications.

Chromium raises the transition temperature slightly. In steels having chromium contents in excess of 0.90%, it is very difficult to develop those microstructures and mechanical properties that are typical of plain carbon steels; therefore, impact test results are not comparable. Chromium is usually added to increase hardenability. The increase in hardenability is often sufficient to develop a martensitic microstructure that provides high upper-shelf energy. Medium-carbon, straight chromium alloy steels, such as 5140, are susceptible to embrittlement when quenched to martensite and tempered between 370 and 575 °C (700 and 1070 °F).

Molybdenum in the typical quantities in alloy steels (up to about 0.40%) raises the 50% FATT. Molybdenum is frequently used to increase hardenability, and it influences notch toughness primarily through its effect on microstructure. About 0.5 to 1.0% Mo can be added to alloy steels to reduce their susceptibility to temper embrittlement, but it is effective only for relatively short heating times at embrittling temperatures. Molybdenum appears to delay rather than eliminate temper embrittlement, because steels containing small amounts of this element have become embrittled upon prolonged exposure within the embrittling temperature range.

Boron. For quenched and tempered steels, a practical way of improving toughness without reducing strength is to use a boron-containing grade of steel with a lower carbon content. However, the benefit of boron is applicable only to quenched and tempered steels; boron reduces the toughness of as-rolled, as-annealed, and as-normalized steels.

Copper in steels that have not been subjected to precipitation hardening appears to be moderately beneficial to low-temperature notch toughness. However, copper promotes precipitation hardening in steel and, as a result, may adversely affect notch toughness, particularly if the tempering temperature is between 400 and 565 °C (750 and 1050 °F).

Vanadium, niobium, and titanium are most often used in steels that receive controlled thermomechanical treatment. Consequently, the toughness of steels containing these elements is largely a function of mill processing. When the steel is finished at temperatures below about 925 °C (1700 °F) (which is characteristic of certain HSLA steels), vanadium, niobium, and titanium improve toughness primarily by refining the ferrite grain size. At higher finishing temperatures, these elements may be detrimental to toughness.

Zirconium, titanium, calcium, and the rare earths can be used to control the shape of manganese sulfide inclusions, causing the inclusions to be spherical rather than elongated. Spherical inclusions raise upper-shelf energy and minimize the anisotropic nature of notch toughness; these effects are particularly useful in HSLA sheet and thin plate.

Effects of Manufacturing Practices

Deoxidation Practice. The effect of deoxidation practice on the notch toughness of steels is directly traceable to the presence of those alloying elements and impurities characteristic of the deoxidation practice. Rimmed steels typically contain appreciable quantities of oxygen and nitrogen; soundness and homogeneity of rimmed steel ingots are often poor. These characteristics of rimmed steels account for their poor notch toughness. Killed steels, particularly silicon-aluminum-killed steels, have lower transition temperatures and higher upper-shelf energy values than rimmed steels. Semikilled steels have toughness properties between those of rimmed and killed steels. A comparison of the notch toughness of these three types of steel is shown in Fig. 37.

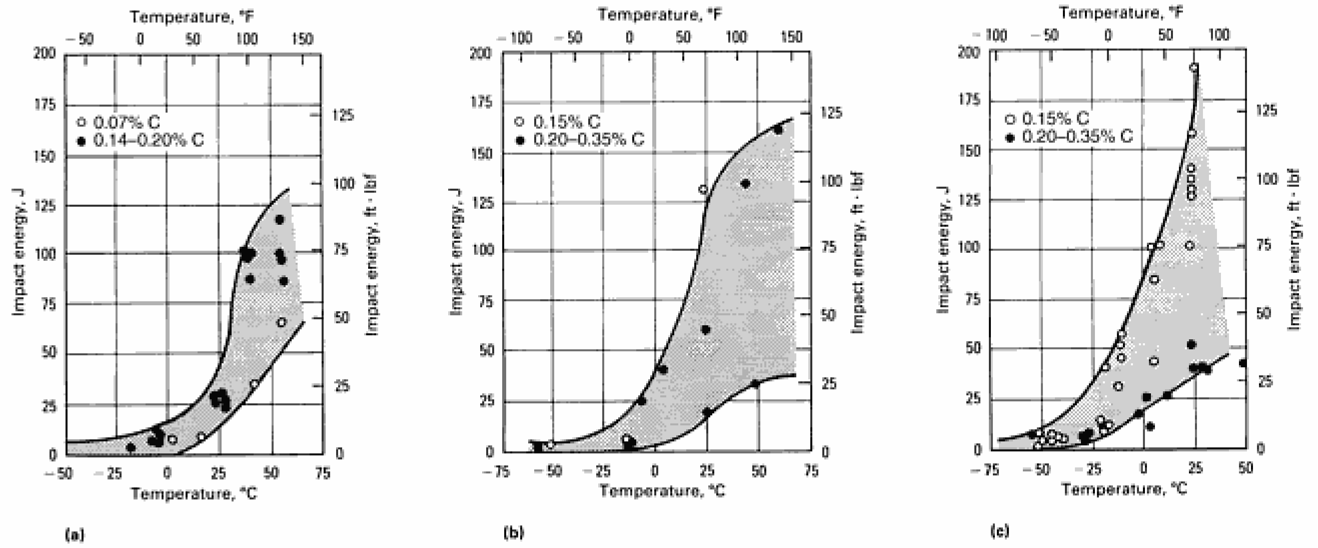


Fig. 37 Effects of deoxidation practice on notch toughness. Charpy V-notch impact energy varies with temperature for (a) rimmed, (b) semikilled, and (c) killed plain carbon steels.

Hot Deformation Temperature. The effect of hot deformation on the notch toughness of steel can be directly related to the microstructure produced during hot rolling and forging. Steels deformed at temperatures above about 980 °C (1800 °F) undergo considerable recrystallization and grain growth during rolling; the structure thus obtained is only slightly affected by the rolling process. The notch toughness of steels deformed at such high temperatures is largely determined by the size to which the austenite grains grow after recrystallization. The influence of grain size on transition temperature is shown in Fig. 38. When steels are deformed at lower temperatures, recrystallization and growth of austenite grains cannot proceed to the extent possible at higher deformation temperatures. Thus, the transition temperature can be significantly lowered by deforming in the lower portion of the austenite temperature range. Figure 39 shows the effect of finishing temperature during hot rolling on the 54 J (40 ft · lbf) transition temperature of a carbon-manganese steel.

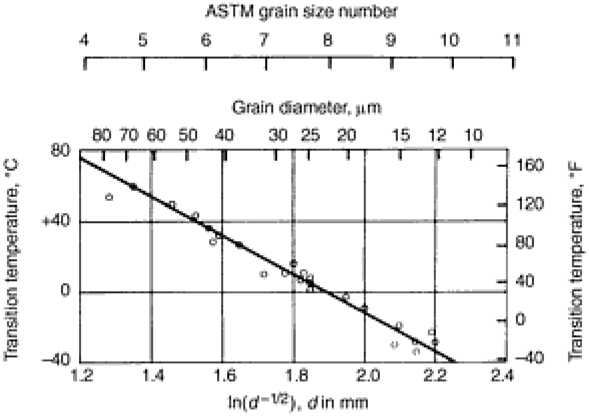


Fig. 38 Effect of grain size on transition temperature. Variation in fracture appearance transition temperature with ferritic grain size for 0.11% C mild steel. Transition temperature varies linearly with ln($d^{-1/2}$) and is lower for fine-grained steel.

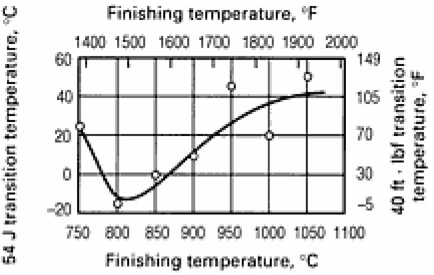


Fig. 39 Effect of finishing temperature on notch toughness. The 54 J (40 ft · lbf) Charpy V-notch transition temperature varies with hot-rolling finishing temperature for silicon-killed 0.24C-1.69Mn steel.

Toughness Anisotropy. Steels can acquire strongly anisotropic microstructures as a result of working. Anisotropic microstructures are often indicative of the anisotropy of mechanical properties, particularly notch toughness. Anisotropy, therefore, is an important consideration in the design and fabrication of rolled, forged, drawn, or extruded steel products.

The effect of anisotropy on the notch toughness of as-rolled low-carbon steel plate is shown in Fig. 40. Specimens parallel to the rolling direction (orientations L-S and L-T) show higher impact energies throughout the ductile-to-brittle fracture transition temperature range than do specimens perpendicular to the rolling direction (orientation T-L). Orientation L-T is the standard longitudinal specimen, and orientation T-L is the standard transverse specimen referred to in ASTM E 23. Therefore, when a part is to be cut from plate, it is essential to specify the orientation of the part relative to the rolling direction.

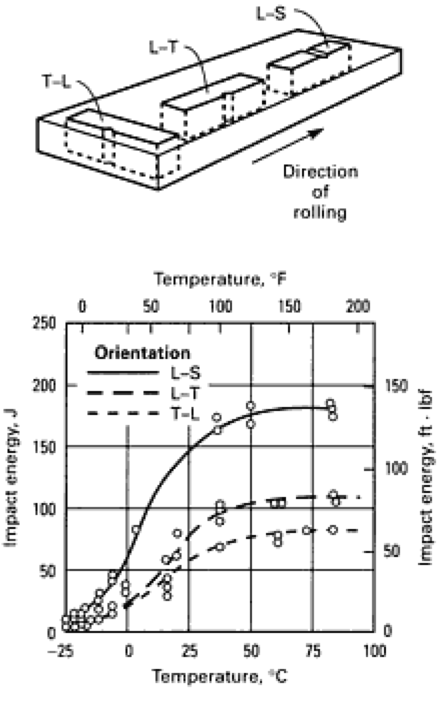


Fig. 40 Variation of Charpy V-notch impact energy with notch orientation and temperature for steel plate containing 0.012% C

The rolling schedule during the fabrication of plate affects anisotropy. For example, if the steel had been cross rolled so that it received about the same amount of hot reduction in both directions, the curves for orientation would nearly coincide at a position between the L-T and T-L curves for material reduced by conventional rolling.

Regardless of the amount of cross rolling, specimens that are notched parallel to the plate surface (orientation L-S) absorb greater amounts of energy than those notched at right angles to the plate surface (orientation L-T). In the experiment described in Fig. 40, the temperature range over which transition occurred (and also the shear-fracture transition temperature) was the same regardless of notch or specimen orientation. In other experiments, transition temperatures for both energy absorption and fracture appearance were higher for transverse orientations than for longitudinal orientations.

Section and Part Size. Variations in fracture behavior can also result from differences in metallurgical structure between thin and thick stock of a given material. For example, the transition temperature of hot rolled low-carbon steel varies with plate thickness, as shown in Fig. 41. In these tests, specimen size was constant, yet ductile-to-brittle energy transition still increased with increasing plate thickness. Reduction of toughness with increasing plate thickness is not limited to low-carbon steel but apparently applies to all steels. Because of the characteristics of normal commercial processing, the metallurgical structure of thick stock is different from that of thin stock, resulting in inherently lower toughness for the thicker stock. More important, the probability that a given part will contain a crack or a flaw of critical size (or greater) increases with increasing stock thickness or part size. The lower inherent toughness of thick stock and the higher probability that thick stock contains a large crack or flaw, combined with the plane-strain conditions inherent in thick members, account for the fact that large structures are more susceptible to brittle fracture than small structures.

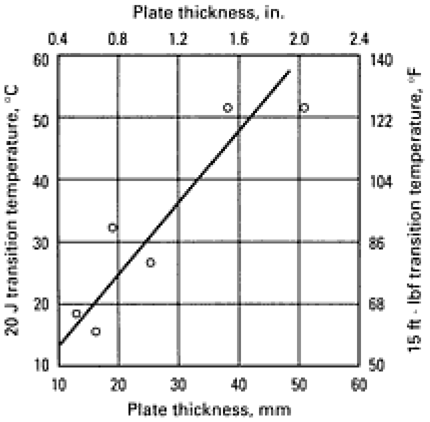


Fig. 41 Effect of plate thickness on notch toughness for aluminum semikilled steel (0.14C-1.25Mn-0.007S-0.020P-0.021Nb)

Effects of Microstructure

Like most mechanical properties, the notch toughness of steel can usually be traced directly to microstructure. Because the microstructures of steel are readily observed and classified, it is convenient to attribute the various mechanical properties to the microstructure, even though the properties might also be attributed to the composition of manufacturing history of the steel.

Microstructural Constituents. In general, of the major microstructural constituents found in steels, pearlite and ferrite have the highest transition temperature, followed by upper bainite and, finally, tempered martensite or lower bainite. Values of notch toughness for similar steels having different carbon contents and microstructural constituents are shown in Fig. 42. To facilitate comparison of the different microstructures, these steels were tempered to uniform strength levels before testing. In practice, the cooling or quenching rate determines the resulting microstructure or mixture of microstructures in a particular steel. The transformation characteristics are controlled by the cooling rate, alloy content, austenitizing temperature, and austenite grain size.

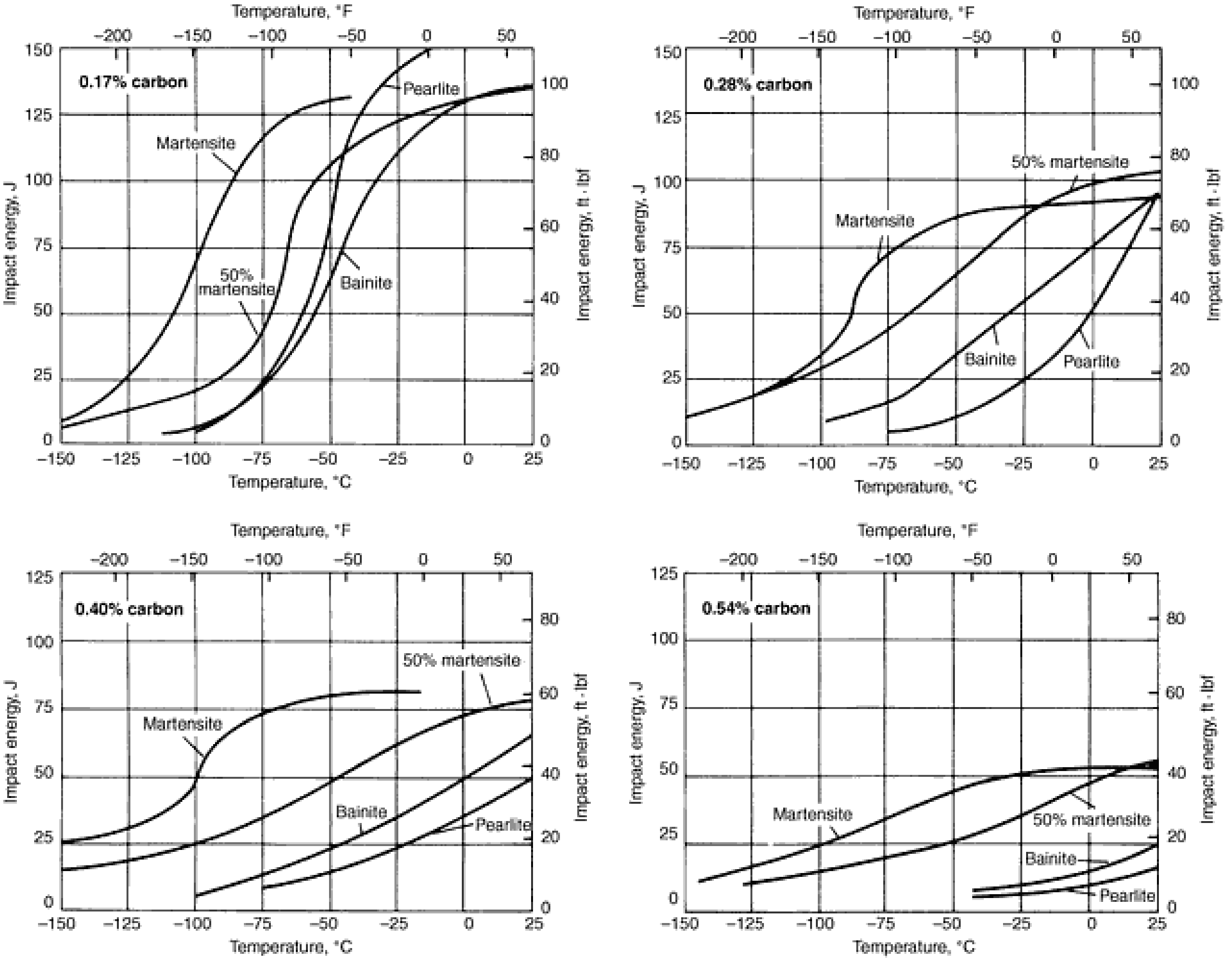


Fig. 42 Effect of microstructure on notch toughness. Variation in Charpy V-notch impact energy with microstructure and carbon content for 0.70% Cr, 0.32% Mo steel. Pearlitic structure was formed by transformation at 650 °C (1200 °F). A structure with 50% martensite was formed by quenching in lead at 450 °C (850 °F) for 10, 19, 35, and 100 s for the 0.17 to 0.54% C steels, respectively. Fully martensitic structures were formed by quenching the 0.17 and 0.28% C grades in water and oil quenching the grades containing 0.40 and 0.54% C. Bainite was formed by quenching in lead at 450 °C (850 °F) and holding 1 h, except that the 0.54% C grade was held 3 h. All specimens were tempered to the same hardness level.

Generally, treatments that produce microstructures with inferior room-temperature toughness also raise transition temperature. Precipitates and second-phase particles are detrimental to toughness, especially if located at grain boundaries. A spheroidization treatment of pearlitic steels can improve toughness by reducing strength and eliminating ferrite lamellae (which have a platelike form and thus are paths of easy cleavage fracture). Spheroidization also improves toughness by changing the shape of the brittle cementite lamella of pearlite to innocuous spherical particles. In addition, steels can lose toughness because of various embrittlement phenomena such as temper embrittlement.

Steels having a tempered martensitic or a lower bainitic structure offer an optimum balance of strength and toughness. When observed under a light microscope, these two microconstituents are indistinguishable. Only by transmission electron microscopy can one distinguish tempered martensite from lower bainite. Which of these two microconstituents provides better notch toughness has been a subject of controversy.

Isothermally transformed lower bainite has superior toughness, and a slightly lower transition temperature, than tempered martensite of the same strength (see Fig. 43). However, mixed structures, which result from incomplete bainitic treatments causing partial transformation to martensite, have lower toughness and much higher transition temperatures than either 100% tempered martensite or 100% lower bainite. Thus, it is important that bainitic treatments be carried to completion to avoid the adverse effects of mixed structure.

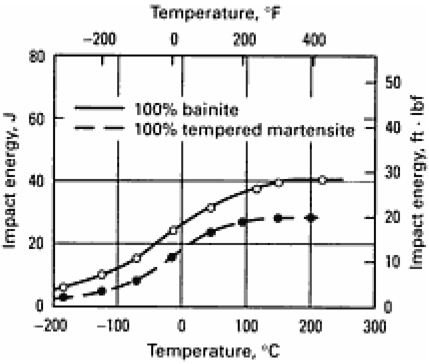


Fig. 43 Variation in Charpy V-notch impact energy with temperature for specimens of 4340 steel having 100% tempered martensite and 100% bainite microstructures. All specimens were austenitized for 30 min at 845 °C (1550 °F) in neutral salt. 100% bainite was produced by isothermal transformation for 1 h at 315 °C (600 °F) in agitated salt. 100% tempered martensite was produced by quenching in agitated oil at 50 to 55 °C (120 to 135 °F) and tempering at 315 °C (600 °F). All specimens had the same tensile strength.

Finally, the presence of austenite inhibits the fast propagation of cleavage fracture in some ferritic and martensitic steels.

Fracture Toughness of Steels

FRACTURE-MECHANICS TECHNOLOGY has significantly improved the ability to design safe and reliable structures. The application of fracture-mechanics concepts has identified and quantified the primary parameters that affect structural integrity. These parameters include the magnitude and range of the applied stresses; the size, shape orientation, and rate of propagation of the existing crack; and the fracture toughness of the material.

Linear-elastic fracture-mechanics technology is based on an analytical procedure that relates the stress-field magnitude and distribution in the vicinity of a crack tip to the nominal stress applied to the structure; to the size, shape, and orientation of the crack or cracklike imperfection; and to the material properties. The stress-field equations show that the magnitude of the elastic stress field can be described by a single parameter, K, which is designated the "stress-intensity factor," as will be briefly described below.

Fracture Toughness Properties

Because fracture mechanics properties are being examined for a broad spectrum of steels with extreme variations in strength, composition, and microstructure, this article will also attempt to present typical data for several classes of steels including:

- Ferrite-pearlite steels (plain carbon, carbon-manganese, and HSLA steels) with nominal yield strengths ranging from approximately 240 to 470 MPa (35 to 70 ksi)
- Quenched-and-tempered alloy steels (low and medium carbon content) with yield strength levels ranging from approximately 600 to 900 MPa (90 to 130 ksi)
- Ultrahigh-strength steels with yield strength levels approaching or exceeding approximately 1400 MPa (200 ksi) depending on the heat treatment. This group includes medium-carbon quenched-and-tempered steels, high fracture toughness Fe-Ni-Co steels, and 18% Ni maraging steels

Additional information on these steels, including compositions, applicable specifications, and minimum mechanical property requirements, can be found in other articles contained within this Section.

Fracture Toughness versus Yield Strength. The relationship between fracture toughness and yield strength for the three steel classes listed above is shown in Fig. 45. As this figure indicates, fracture toughness generally decreases with increasing yield strength for higher strength steels, and high-fracture-toughness steels have ductile (low-carbon) martensite and retained metastable austenite as dominant phases in the microstructure. Steels that contain predominantly ferritic and pearlitic structures have relatively low fracture toughness. Table 6 summarizes the effects of microstructure on toughness.

Table 6 Effects of microstructural variables on fracture toughness of steels

Microstructural parameter	Effect on toughness
Grain size	**Decrease in grain size increases K_{Ic} in austenitic and ferritic steels**
Unalloyed retained austenite	**Marginal increase in K_{Ic} by crack blunting**
Alloyed retained austenite	**Significant increase in K_{Ic} by transformation-induced toughening**
Interlath and intralath carbides	**Decrease K_{Ic} by increasing the tendency to cleave**
Impurities (P, S, As, Sn)	**Decrease K_{Ic} by temper embrittlement**
Sulfide inclusions and coarse carbides	**Decrease K_{Ic} by promoting crack or void nucleation**
High carbon content (>0.25%)	**Decrease K_{Ic} by easily nucleating cleavage**
Twinned martensite	**Decrease K_{Ic} due to brittleness**
Martensite content in quenched steels	**Increase K_{Ic}**
Ferrite and pearlite in quenched steels	**Decrease K_{Ic} of martensitic steels**

Source: Ref 6

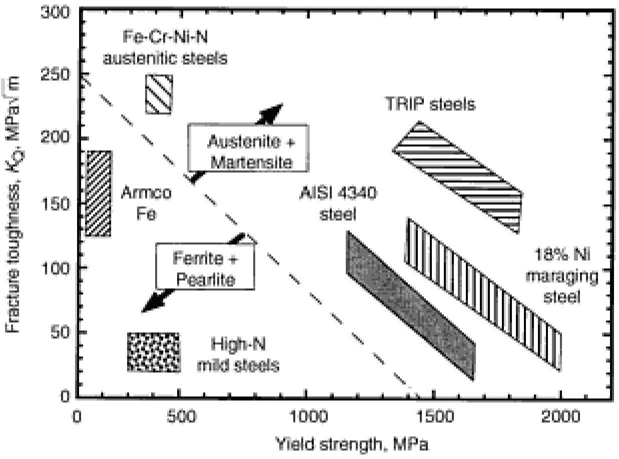


Fig. 45 Fracture toughness as a function of yield strength for structural steels. K_Q, provisional K_{Ic} value. TRIP,

transformation-induced plasticity. Source: Ref 6

Effects of Alloy Chemistry. The influence of alloying additions on fracture toughness can be appreciated by comparing the toughness values of the quenched-and-tempered steel (4340) with those of the maraging steel. The major alloying chemistry differences here are carbon content, which is low for the maraging steels (0.03%) but higher for the quenched-and-tempered steels (more than 0.25%); nickel content, which is 18% for maraging steels; and titanium content, which is added as a strengthener in maraging steels. As a generalization, it may be inferred that carbon and strong carbide formers tend to decrease toughness in ultrahigh-strength steels.

Because alloy chemistry affects other characteristics such as hardenability, tempering response, strength, and ductility (Ref 7), it is very difficult to separate the effects of chemistry on fracture toughness from the effects of other variables. In one series of experiments in which strength was held constant (Ref 8, 9), an increase in nickel content of about 5% increased fracture toughness by about 50% in the transition, temperature range, as shown in Fig. 46(a). Here, the yield strength was 1175 MPa (170 ksi) at room temperature. On the other hand, for lower-strength steels with yield strengths ranging from 500 to 700 MPa (73 to 102 ksi) at -100 °C (-150 °F), addition of 3.5% Ni increased fracture toughness by more than 100% (Ref 10). This is illustrated in Fig. 46(b). It should be noted that moderate additions of nickel mainly improve low-temperature fracture toughness through resistance to cleavage, and that little effect may be seen at higher temperatures at which microvoid coalescence is the fracture mode. Such is the case in Fig. 46(a) at temperatures in the upper-shelf region.

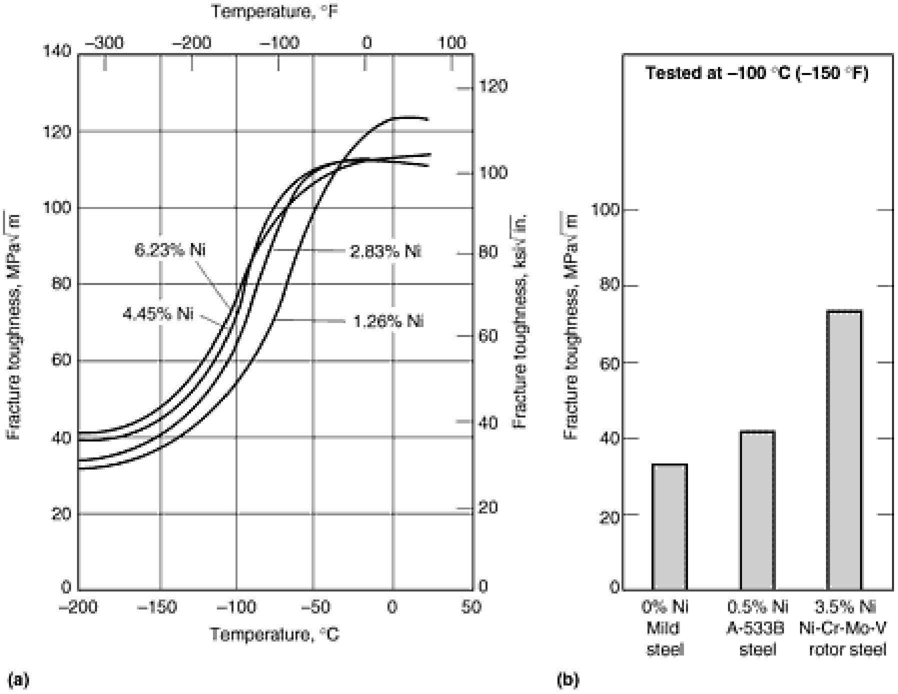


Fig. 46 Effect of nickel content on fracture toughness of several steels. (a) High-strength steels containing 0.35% C, 0.65% Mn, 0.35% Si, 0.80% Cr, 0.30% Mo, 0.10% V, and various amounts of nickel; all steels hardened to a yield strength of 1175 MPa (170 ksi). Source: Ref 8, 9. (b) Lower-strength steels (those containing 0 and 0.5% Ni) with yield strengths ranging from 500 to 700 MPa (73 to 102 ksi) at -100 °C (-150 °F). Source: Ref 10

It is well known that decreasing the carbon content decreases the transition temperature in ferrite-pearlite steels. This trend is less prevalent in ultrahigh-strength steels if strength is maintained at a constant level by tempering. The effect of carbon content on the fracture toughness transition curves for alloy steels containing 0.28, 0.35, and 0.41% C, with strength maintained at 1175 MPa (170 ksi), is illustrated in Fig. 47. There is little effect in the transition temperature range; however, there is a substantial effect in the upper-shelf region, where microvoid coalescence (ductile rupture) is the fracture mode.

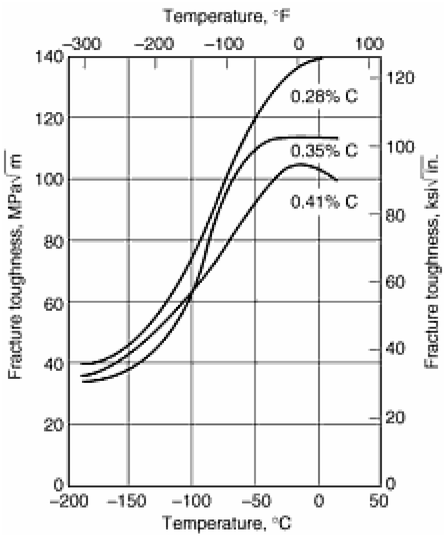


Fig. 47 Effect of carbon content and testing temperature on fracture toughness of alloy steels. Data are for steels containing 0.65% Mn, 0.35% Si, 0.80% Cr, 3.00% Ni, 0.30% Mo, 0.10% V, and various amounts of carbon; all steels were hardened and tempered to a yield strength of approximately 1175 MPa (170 ksi). Source: Ref 8, 9

Effects of Inclusion Content. Nonmetallic inclusions (single inclusions or cluster of inclusions) reduce fracture toughness, particularly at high strength levels. The effect of sulfide inclusion content (which is a function of sulfur content) on fracture toughness of 4345 steel is shown in Fig. 48. Because of this effect, special melting and processing requirements are often specified when alloy steels are selected for certain critical applications, such as aircraft landing gear. Vacuum arc remelting (VAR), vacuum induction melting (VIM), and electroslag remelting (ESR) are three of the special processes that normally produce cleaner steels than more common steelmaking processes (see the article "Steelmaking Practices and Their Influence on Properties" in this Handbook).

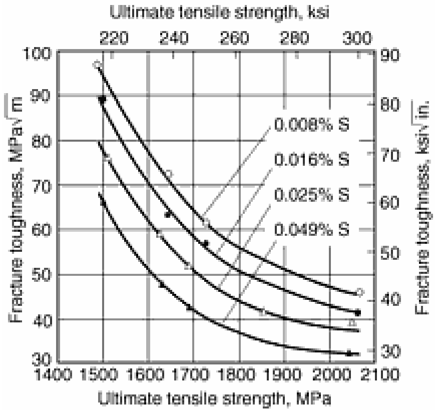


Fig. 48 Effect of sulfur content on fracture toughness of 4345 steel hardened and tempered to various strength levels. Source: Ref 11

Not only does sulfur affect ultrahigh-strength steels, but it may also effect grades of low-to-medium strengths (Ref 12). This is largely a microvoid nucleation mechanism, and, if the sulfide inclusion length is plotted versus crack tip opening displacement (CTOD), an inverse relationship is revealed, as shown in Fig. 49(a). The critical crack tip opening displacement, δ_c, is a measure of fracture toughness. Under plane-strain conditions, an approximate relation between δ_c and K_{Ic} is:

$$\delta_c \cong \frac{K_{Ic}^2}{2\sigma_{ys}E} \qquad \text{(Eq 3)}$$

where σ_{ys} is yield strength and E is Young's modulus. Thus, one means of improving toughness is to reduce the projected inclusion length by controlling the shape of the inclusions (Ref 12). This can be achieved by adding rare earths, which combine with manganese sulfide to form hard-to-deform particles comprised of sulfides, oxides, and/or oxysulfides. This means of shape control greatly improves transverse notch impact properties, as shown in Fig. 49(b) for X-65 pipeline steel (Ref 13). As shown in Fig. 49(c), notch toughness of a large heat of pipeline steel tended to increase with increasing rare earth metal additions (Ref 14). With regard to shape control, Luyckx et al. (Ref 15) demonstrated that when there was a complete change from elongated to globular sulfides, at a cerium-to-sulfur ratio of two, the upper-shelf impact energy became a maximum. This is seen in Fig. 49(d). As might be expected, there was little effect on rare earth metal additions on longitudinal properties, because the shape of sulfides is not particularly detrimental to longitudinal fracture toughness in steels of low to medium strength.

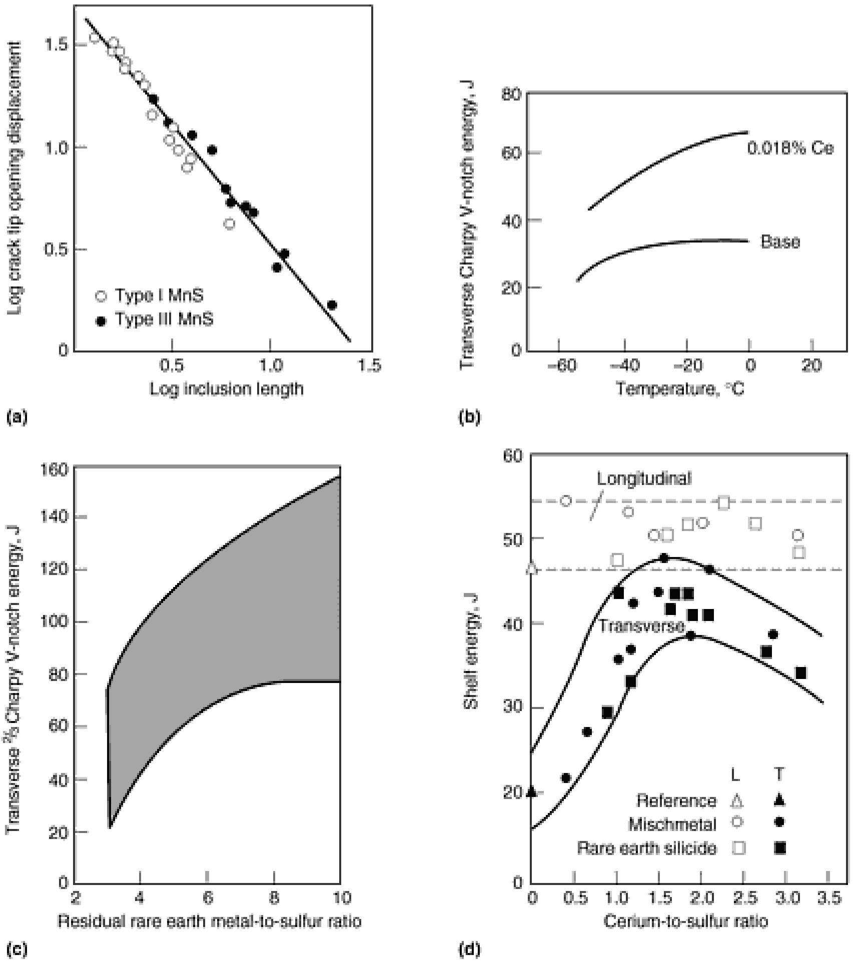


Fig. 49 Effect of sulfide inclusions on toughness of ferritic steels. (a) Relationship between projected inclusion length per unit area and crack tip opening displacement to fracture in sulfur-bearing steels. (b) Effect of rare earth additions on impact properties of aluminum-silicon killed X-65 pipeline steel. (c) Relationship between transverse Charpy V-notch (CVN) energy and rare earth metal sulfur ratio ($\frac{2}{3}$-size Charpy specimens) at -18 °C (-1 °F). (d) Relationship between shelf energy determined on longitudinal and transverse $\frac{1}{2}$-size Charpy V-notch specimens and cerium-to-sulfur ratio. L, longitudinal; T, transverse. Source: Ref 12

Effects of Trace Elements. Other alloy chemistry effects are those that cause or influence temper embrittlement. As indicated in Table 6, impurities such as phosphorus, silicon, arsenic, and tin reduce K_{Ic} values because of their contributing to temper embrittlement. Additional information on this embrittlement mechanism can be found elsewhere in this Handbook.

Effects of Microstructure and Heat Treatment. Typical microstructural changes on heat treatment of high-strength steels are accomplished by changing the austenitizing temperature and time at temperature, the quenching rate, and the tempering temperature and time at temperature. Increasing the austenitizing temperature and time has a two-fold effect in that it increases the grain size and/or increases the solutionizing of alloy carbide formers. The former effect may produce mixed results in that austenitizing at 1200 °C (2200 °F) can increase the sharp-crack fracture toughness of an AISI 4340 steel over that obtained using conventional heat treatments; however, the large prior austenite grains may produce a lower impact toughness (Ref 16). Increased prior austenite grain size in high-strength steels may also have a detrimental effect on resistance to fatigue cracking (Ref 17). On the other hand, it is well known that reasonable austenitizing temperatures and times are necessary to dissolve the carbide-forming elements prior to quenching.

Variations in quenching rates also influence fracture toughness of alloy steels by causing variations in the as-quenched microstructures. Quenching alloy steels in oil to obtain nearly 100% martensite on quenching will result in higher fracture toughness in the tempered condition than will slack quenching and tempering at the same temperature. This condition is discussed by Peterman and Jones (Ref 18) for heat-treated aircraft structures of D-6ac steel. Briefly, austenitizing at 900 °C (1650 °F), quenching in salt at 200 °C (400 °F), and tempering at 200 °C resulted in an average fracture toughness (K_{Ic}) of 57 MPa$\sqrt{m}$ (52 ksi$\sqrt{in.}$), whereas austenitizing at 925 °C (1700 °F), quenching in oil at 60 °C (140 °F), and tempering at 200 °C (400 °F) resulted in an average fracture toughness of 101 MPa$\sqrt{m}$ (92 ksi$\sqrt{in.}$).

The effects of tempering ultrahigh-strength steels at temperatures in the upper portion of the tempering range are to increase fracture toughness and to reduce yield strength. In the intermediate tempering temperature regime between 200 and 400 °C (400 and 750 °F), these effects are not always apparent. This is shown in Fig. 50(a), where fracture toughness at 25 °C (75 °F) is relatively independent of tempering temperature for three different nickel additions. For tests at -73 °C (-100 °F), however, severe tempered martensite embrittlement results for the low-nickel steel tempered at 300 °C (570 °F). This embrittlement is partly reduced by addition of 3% Ni and completely suppressed by addition of 6% Ni, as indicated in Fig. 50(b).

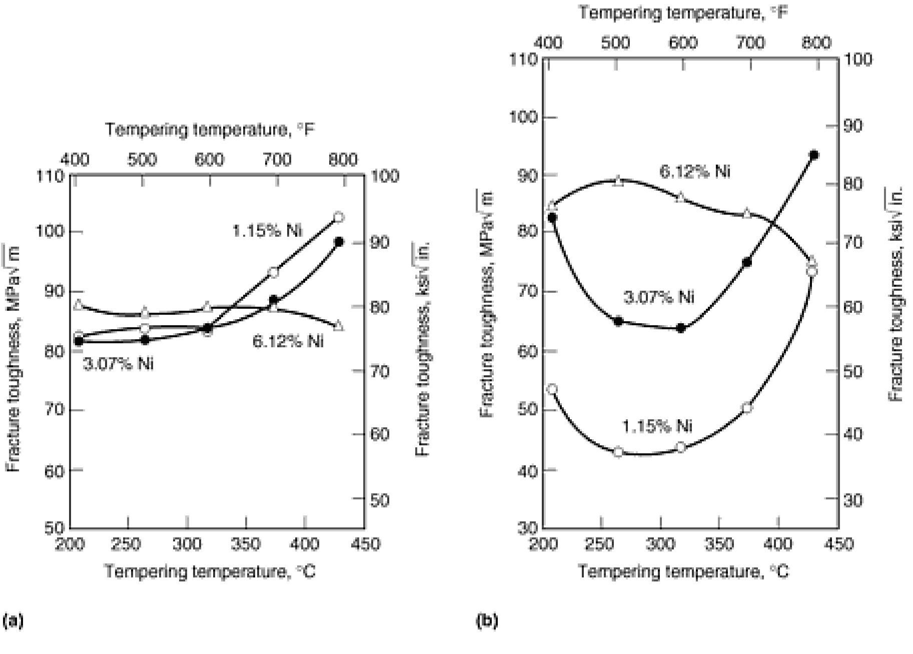


Fig. 50 Variation of notch-bend fracture toughness with tempering temperature for steels containing 0.35% C, 0.65% Mn, 0.35% Si, 0.80% Cr, 0.30% Mo, 0.10% V, and various amounts of nickel. (a) Measurements made at 25 °C (75 °F). Source: Ref 9. (b) Measurements made at -73 °C (-100 °F). Source: Ref 8

For lower-strength steels, useful microstructural modifications to improve low-temperature fracture toughness involve decreasing of the ferrite or prior austenite grain size. Results from two investigations presented in Fig. 51 show that, for temperatures above -150 °C (-240 °F), a substantial improvement in fracture toughness can be achieved through grain refinement (Ref 9, 19). Here, it is indicated that there may be a relationship between K_{Ic} and grain size, ***d***. This is shown for both ferrite grain size (Ref 20) and prior austenite grain size (Ref 21) in Fig. 52(a) and 52(b) respectively. It is clear, then, that one goal for improved low-temperature fracture toughness in steels of low to medium strength is a refined grain size such as has been achieved in HSLA steels. The development of fine grain size in these steels through the use of minor alloying additions and lower hot rolling finishing temperatures has resulted in large improvements in fracture toughness.

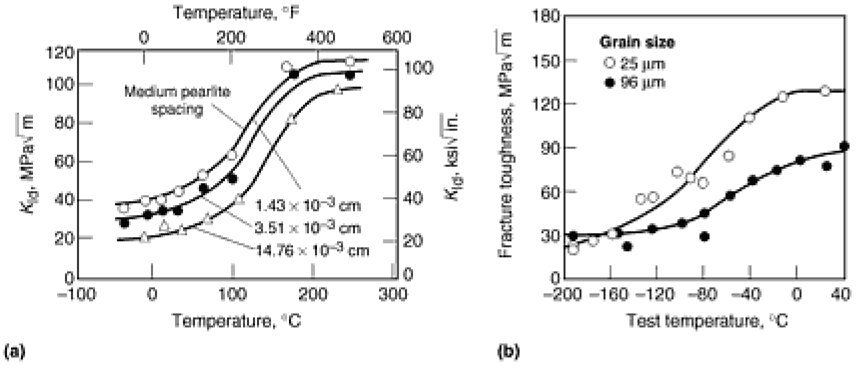


Fig. 51 Effect of grain size on fracture toughness. (a) Dynamic fracture toughness (K_{Id}) curves for fully pearlitic steels as a function of temperature for three prior austenite grain sizes. (b) Fracture toughness as a function of temperature for St 37-3 steel (Fe-0.08C-0.45Mn) in two grain sizes. Source: Ref 9, 19

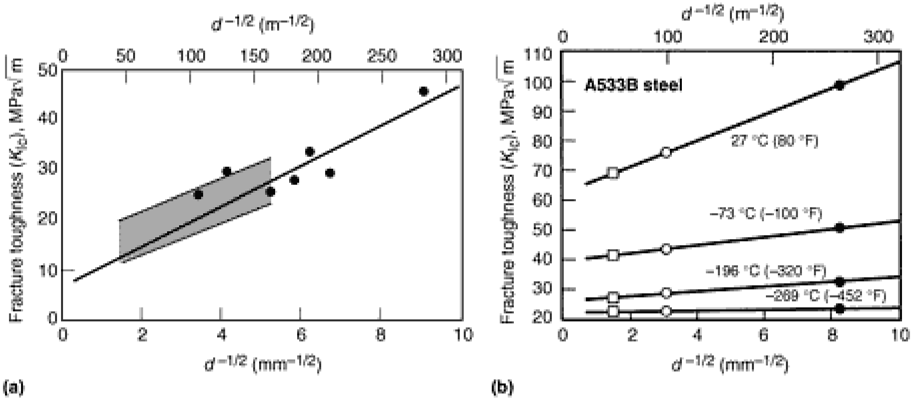


Fig. 52 Relationship of fracture toughness to inverse square root of grain size. (a) Fracture toughness of several plain carbon steels versus reciprocal square root of ferrite grain size at -120 °C (-184 °F). Source: Ref 20. (b) Dependence of fracture toughness on prior austenite grain size at four different temperatures. Source: Ref 21

Effect of Strain Rate. Not only does the fracture toughness temperature transition change with alloy composition and yield strength, but it also changes with loading rate. This is extremely important in low-strength and medium-strength steels, which are strain-rate sensitive. Such a result is shown in Fig. 53, where it is seen that A 36 steel undergoes a temperature transition shift as the strain rate increases from 10^{-5} to 10^{-3} to $10 s^{-1}$. Obviously, it would be very dangerous to select such a steel for dynamic conditions based on static fracture toughness unless the temperature shift could be adequately described. A series of studies (Ref 23, 24, 25) has shown that the magnitude of this shift is dependent on yield strength. Barsom (Ref 24) has described this relationship as:

$$T_{\text{shift}} \text{ (in °C)} = 119 - 0.12\sigma_{ys} \qquad \textbf{(Eq 4)}$$

for steels with strengths given by 250 MPa $<\sigma_{ys}<$965 MPa (36 ksi $<\sigma_{ys}<$139 ksi), As can be seen in Fig. 54, there is no temperature transition shift for steels with yield strengths greater than about 965 MPa (139 ksi). This has also been verified by Priest (Ref 10) in a large number of tests of low-to-medium-strength steels, some of which are illustrated in Fig. 55. Here, up to six test temperatures and six orders of magnitude of loading rate (K, MPa$\sqrt{\text{m}}\cdot s^{-1}$) were used to determine fracture toughness. It can be seen that there are substantial shifts for low-strength steels. However, for the steel with a yield strength of 970 MPa (140 ksi) in Fig. 55(d), although there is a change in fracture toughness with test temperature, there is no shift with loading rate. For steels with strengths less than 965 MPa (139 ksi), Barsom (Ref 22) has described the combined effect of yield strength and strain rate in the range of $10^{-3}\ s^{-1} \leq \dot{\varepsilon} \leq 10 s^{-1}$ by:

$$T_{\text{shift}}\ (\text{in }^{\circ}\text{C}) = (83 - 0.08\sigma_{ys})\dot{\varepsilon}^{0.17} \qquad \textbf{(Eq 5)}$$

where $\dot{\varepsilon}$ is in s^{-1} units.

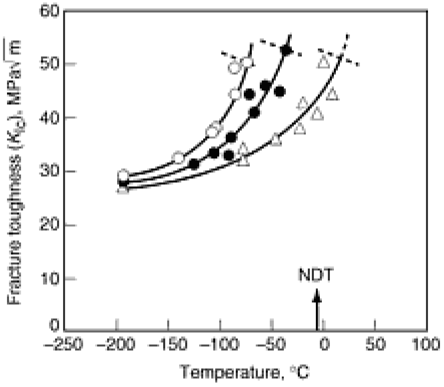


Fig. 53 Effect of temperature and strain rate on fracture toughness of ASTM A 36 steel. The open circles represent K_{Ic} loading ($\dot{\varepsilon} \cong 10^{-5}\ s^{-1}$); the closed circles represent intermediate strain rate loading ($\dot{\varepsilon} \cong 10^{-3}\ s^{-1}$); the open triangles represent dynamic loading ($\dot{\varepsilon} \cong 10\ s^{-1}$). Source: Ref 22

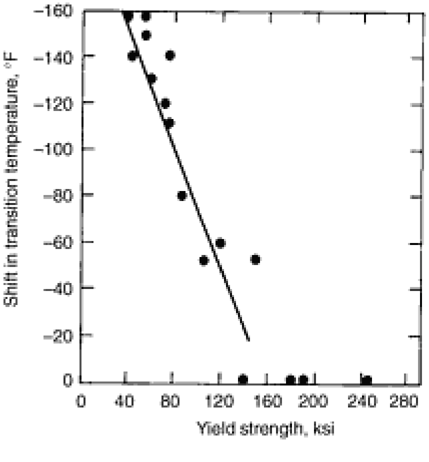


Fig. 54 Effect of yield strength on the shift in transition temperature between impact and static plane-strain fracture-toughness curves. Source: Ref 22

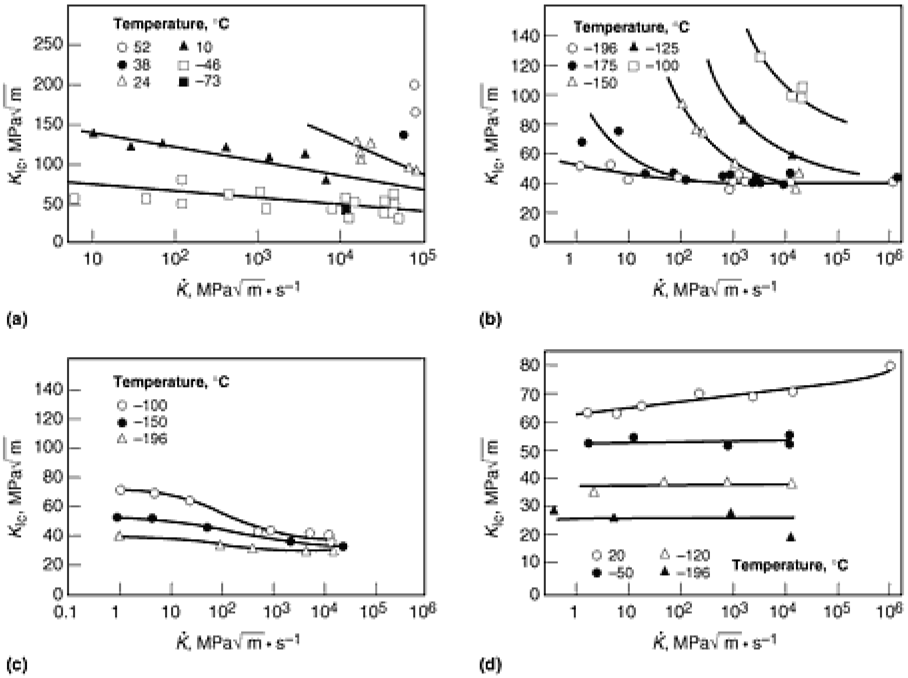


Fig. 55 Influence of temperature and loading rate on fracture toughness. (a) A533B steel; $\sigma_{ys} \cong 450$ MPa (65 ksi). (b) Quenched-and-tempered 0.18C-1.2Mn-0.9Cr-1.1Ni-0.45Mo-0.07V steel; $\sigma_{ys} \cong 600$ MPa (87 ksi). (c) 0.3C-3.5Ni-1.7Cr-0.6Mo-0.15V rotor forging steel; $\sigma_{ys} \cong 670$ MPa (97 ksi). (d) 0.4C-9Ni-4Co steel; $\sigma_{ys} \cong 970$ MPa (140 ksi). Yield strengths reported are at room temperature. Source: Ref 10

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Corrosion Characteristics of Carbon and Alloy Steels

Types of Corrosive Environments

CORROSION OF METALS is defined as deterioration caused by chemical or electrochemical reaction of the metal with its environment. Usually, the corroding medium is a liquid, but gases and solids can also act as corroding media.

Corroding media are generally classified as aqueous or nonaqueous. Aqueous media include all types of water--natural, purified, and contaminated--ranging from deionized and distilled waters, which contain relatively few dissolved substances, through natural fresh waters, which may contain up to 10,000 ppm or more of various minerals or pollutants, to mine waters, deep-well brines, seawater, and certain process waters, which may contain several percent of one or more dissolved chemical substances such as acids, bases, salts, and gases.

Nonaqueous corrodents include dry gases, organic liquids, and liquid metals.

Corrosion by Aqueous Media

Wherever water is involved, corrosion of iron and steel can be presumed to proceed by electrochemical action--that is, local anodic (active) and cathodic (noble) sites develop on the surface of the metal, and corrosion (oxidation) occurs at the anodic sites: $Fe^0 \rightarrow Fe^{2+} + 2e^-$. At the cathodic sites, a reduction reaction occurs which, depending on the pH of the environment, can be hydrogen evolution ($2H^+ + 2e^- \rightarrow H_2 \uparrow$) or oxygen reduction [$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$]. The electrodes liberated at the anode flow through the metal to the cathodic sites, where they are consumed by the cathodic reaction. In near-neutral or alkaline pH solutions, some dissolved oxygen or other reducible species must be present to support the cathodic reaction in order for appreciable corrosion to occur. The presence of dissolved salts generally increases corrosion rate, because it increases the conductivity of the solution and thus increases corrosion currents.

Galvanic cells can be set up by placing iron or steel in an aqueous solution while the ferrous metal is in electrical contact with another metal whose galvanic potential is more noble (more cathodic) than that of the ferrous metal. In this case a larger portion of the surface of the ferrous metal becomes anodic, and corrosion rate increases. Cells also can be set up when a local area of a ferrous metal is shielded from contact with water containing oxygen; this is called oxygen concentration-cell corrosion or crevice corrosion (because it is often seen in crevices, where oxygen is available at the edge of the crevice but is effectively absent within the crevice).

Water is the active corrodent even for some media that are not considered aqueous. Corrosion of ferrous metals in air increases when the surface is moistened regularly, as occurs in locations where dew regularly forms at night.

Corrosion by Nonaqueous Media

Corrosion by most nonaqueous media except liquid metals occurs most often by direct chemical action resulting in loss of metal (e.g., high-temperature oxidation in air) or formation of a converted surface layer (e.g., carburization, nitriding). Most dry gases and organic liquids are noncorrosive to steel at ordinary temperatures, but can become corrosive at elevated temperatures.

Corrosion in liquid-metal systems almost always involves some form of dissolution or leaching, in which atoms leave the solid surface, and go into solution in the liquid metal. In a flowing system, particularly a recirculating system, the corrosion process is often controlled by the difference in temperature between the hottest and coldest points in the system, because solubility is greater as temperature increases.

Carbon and low-alloy steels can be embrittled by contact with liquid brass, aluminum bronze, copper, zinc, lead-tin solders, lithium, cadmium, and indium. The degree of embrittlement is greater for steels that have been heat treated or alloyed to produce higher strength.

Atmospheric Corrosion

ALL UNPROTECTED carbon and alloy steels corrode to some extent when exposed to the atmosphere. The corrosion process can occur relatively rapidly for unalloyed iron, especially in moist air containing specific airborne contaminants. The addition of certain alloying elements--notably silicon, copper, chromium, and nickel--slows the rate of corrosion. The degree of effectiveness of each alloying element on slowing corrosion depends on both the climatic conditions of exposure and the amount of the alloying element present.

Atmospheric corrosion of ferrous metals proceeds by an electrochemical reaction in which the electrolyte is based on moisture from the air--either moisture that falls as precipitation or moisture that condenses as dew on exposed surfaces when the temperature of relatively humid air decreases.

Geographic and Meteorological Factors

It is generally accepted that the principal environmental contaminants responsible for increased ferrous-metal corrosion in urban areas are the gaseous sulfur oxides that originate from the combustion of fossil fuels. The airborne seawater particles that originate in the ocean are responsible for accelerated corrosion in coastal areas. Airborne salts from arid soils of the western states and windborne fertilizer plus silicious and calcareous dust from midwestern rural areas likewise accelerate the atmospheric corrosion of ferrous metals. Complementing these ionic materials are nonionic dust particles that serve as nuclei for condensing dew.

Role of Dew

Dew condensate can be a major factor in promoting corrosion. Condensed dew from a semi-industrial location was reported to have a pH of 4.5; rainwater plus dew collected from a gutter in an eastern industrial location had a pH of 3.5. Such values are sufficiently acidic to stimulate the corrosion of carbon steel through acid attack. Dew cleans the atmosphere by nucleating on particulate matter, dissolving gaseous contaminants, and subsequently clearing both from the air as it condenses on surfaces. Unfortunately, such condensed dew is damaging to both metals and concrete.

Carbon Steels

For many years, Committee A-5 of ASTM (formerly the American Society for Testing and Materials) has exposed carbon steel specimens for the calibration of various test sites. From 1960 to 1964, specimens of carbon steel were exposed for periods of 1 and 2 years in 46 locations, 14 of which were in foreign countries. The locations ranged from tropical to polar, industrial to rural, and marine to arid. The average corrosion rates for two year exposures are given in Table 1 for 34 of the 46 locations. The greatest difference in corrosivity is the 1400-fold span between polar Norman Wells and near-tropical Cape Kennedy (beach site). The span between arid, rural Phoenix and rural State College shows a fivefold difference in corrosivity. A twofold difference exists between rural State College and industrial Newark. These data offer a preliminary appraisal of the atmospheric corrosion that might be expected when unprotected carbon steel structures are exposed in a particular location.

Table 1 Corrosion rates of carbon steel at various locations

Location	**Type of environment**	Corrosion rate[(a)]	
		μm/yr	mils/yr
Norman Wells, NWT, Canada	Polar	0.76	**0.03**
Phoenix, AZ	Rural arid	4.6	**0.18**
Esquimalt, Vancouver Island, BC, Canada	Rural marine	13	**0.5**
Detroit, MI	Industrial	14.5	**0.57**
Fort Amidor Pier, CZ	Marine	14.5	**0.57**
Morenci, MI	Urban	19.5	**0.77**
Potter County, PA	Rural	20	**0.8**
Waterbury, CT	Industrial	22.8	**0.89**
State College, PA	Rural	23	**0.9**
Montreal, QC, Canada	Urban	23	**0.9**
Durham, NH	Rural	28	**1.1**
Middletown, OH	Semi-industrial	28	**1.1**
Pittsburgh, PA	Industrial	30	**1.2**
Columbus, OH	Industrial	33	**1.3**

Trail, BC, Canada	Industrial	33	**1.3**
Cleveland, OH	Industrial	38	**1.5**
Bethleham, PA	Industrial	38	**1.5**
London, Battersea, England	Industrial	46	**1.8**
Monroeville, PA	Semi-industrial	48	**1.9**
Newark, NJ	Industrial	51	**2.0**
Manila, Philippine Islands	Tropical marine	51	**2.0**
Limon Bay, Panama, CZ	Tropical marine	61	**2.4**
Bayonne, NJ	Industrial	79	**3.1**
East Chicago, IN	Industrial	84	**3.3**
Brazos River, TX	Industrial marine	94	**3.7**
Cape Kennedy, FL (60 ft elev., 60 yd from ocean)	Marine	132	**5.2**
Kure Beach, NC (800 ft from ocean)	Marine	147	**5.8**
Cape Kennedy, FL (30 ft elev., 60 yd from ocean)	Marine	165	**6.5**
Daytona Beach, FL	Marine	295	**11.6**
Cape Kennedy, FL (ground level, 60 yd from ocean)	Marine	442	**17.4**
Point Reyes, CA	Marine	500	**19.7**
Kure Beach, NC (80 ft from ocean)	Marine	533	**21.0**
Galeta Point Beach, Panama, CZ	Marine	686	**27.0**
Cape Kennedy, FL (beach)	**Marine**	**1070**	**42.0**

(a) Two-year average

High-Strength Low-Alloy (HSLA) Steels

One of the significant observations that led to the development of high-strength low-alloy steels was the improved atmospheric corrosion resistance exhibited by carbon steel containing 0.05 to 0.2% copper. D.M. Buck performed one of the earliest systematic studies (1913), in which two levels of copper (0.15 and 0.25%) were added to corrugated carbon steel sheets used in 18° inclined roofs for outdoor structures. Weight-loss specimens were exposed simultaneously. The results from three environments--severe industrial, marine, and rural--indicated that copper reduced corrosion. In the industrial location, copper-bearing steel lost 40 to 48% less weight than did copper-free steel. In the marine environment, copper-bearing steel lost 51 to 61% less weight than copper-free steel.

Effect of Composition. Corrosion test results from a systematic study, involving 15.5 years of atmospheric exposure of 270 steels in three environments, were reported by Larrabee and Coburn. The alloying elements studied were copper, nickel, chromium, silicon, and phosphorus, all at levels of less than 1.3%. All these alloying elements were found to be beneficial, with the greatest change in corrosion resistance being caused by increasing copper content. The industrial site was at Kearny, NJ, the semirural site at South Bend, PA, and the marine site at Kure Beach, NC, about 240 m (800 ft) from the ocean. Some of the results of the study at the industrial site are summarized in Fig. 1. The "HSLA steel" (bottom curve) was comparable to ASTM A 242, which covers architectural grade copper-bearing weathering steels.

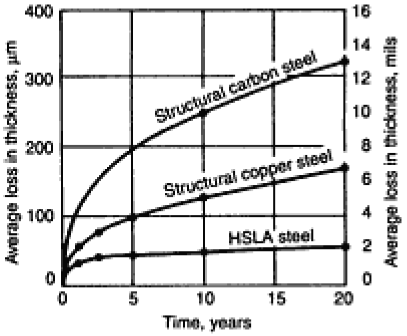


Fig. 1 Atmospheric corrosion versus time in a semi-industrial or industrial environment

Corrosion in Selected Environments. Table 2 compares carbon steel with copper-bearing steel and proprietary HSLA steels of the ASTM types A 242, A 588, A 514, and A 517 in various rural, industrial, and marine environments. A significant improvement in performance has been achieved by all of the high-strength low-alloy steels in comparison with structural copper steel and structural carbon steel.

Table 2 Corrosion of structural steels in various environments

Type of atmosphere	Average reduction in thickness[(a)], mils						
	Time, yr	**Structural carbon steel**	**Structural copper steel**	**UNS K11510[(b)]**	**UNS K11430[(c)]**	**UNS K11630[(d)]**	UNS K11576[(e)]
Industrial (Newark, NJ)	3.5	3.3	2.6	1.3	1.8	1.4	**2.2**
	7.5	4.1	3.2	1.5	2.1	1.7	. . .

	15.5	5.3	4.0	1.8	. . .	2.1	**. . .**
Semi-industrial (Monroeville, PA)	1.5	2.2	1.7	1.1	1.4	1.2	**1.6**
	3.5	3.7	2.5	1.2	2.1	1.4	**2.4**
	7.5	5.1	3.2	1.4	2.4	1.7	**. . .**
	15.5	7.3	4.7	1.8	. . .	1.8	**. . .**
Semi-industrial (South Bend, PA)	1.5	1.8	1.4	1.0	1.3	1.0	**1.5**
	3.5	2.9	2.2	1.3	1.9	1.5	**2.4**
	7.5	4.6	3.2	1.8	2.7	1.9	**. . .**
	15.5	7.0	4.8	2.2	. . .	2.5	**. . .**
Rural (Potter County, PA)	2.5	. . .	1.3	0.8	1.2	. . .	**. . .**
	3.5	2.0	1.7	1.1	1.4	1.2	**1.8**
	7.5	3.0	2.5	1.3	1.5	1.5	**. . .**
	15.5	4.7	3.8	1.4	. . .	2.0	**. . .**
Moderate marine (Kure Beach, NC, 800 ft from ocean)	0.5	0.9	0.8	0.6	0.8	0.7	**1.0**
	1.5	2.3	1.9	1.1	1.7	1.2	**1.7**
	3.5	4.9	3.3	1.8	2.5	1.9	**2.2**
	7.5	5.6	4.5	2.5	3.7	2.9	**. . .**
Severe marine (Kure Beach, NC, 80 ft from ocean)	0.5	7.2	4.3	2.2	3.8	1.1	**0.7**
	2.0	36.0	19.0	3.3	12.2	. . .	**2.1**
	3.5	57.0	38.0	. . .	28.7	3.9	**3.9**
	5.0	**(f)**	**(f)**	**19.4**	**38.8**	**5.0**	**. . .**

(a) To obtain equivalent values in μm, multiply listed value by 25.

(b) ASTM A 242 (type 1).

(c) ASTM A 588 (grade A).

(d) ASTM A 514 (type B) and A 517 (grade B).

(e) ASTM A 514 (type F) and A 517 (grade F).

(f) Specimen corroded completely away.

Soil Corrosion

SOIL CORROSION may be considered to encompass all corrosion taking place on buried structures. Soil corrosion has been ascribed to low pH, stray currents, reactive chemicals, low resistivity, and bacterial action; however, oxygen and water are considered to be the key factors necessary for corrosion.

Soil Characteristics

Soil is a heterogeneous, porous material that ranges in character from soft spongy peats through soft clays, loams, and silts to coarse-grained sands and gravels. There are two large soil classes in the United States; west of the Mississippi River, soils generally accumulate lime and tend to be alkaline, whereas east of the Mississippi they do not and, therefore, tend to be acidic. Soil classes may be subdivided into texture groups containing varying amounts of clay, silt, and sand. Well-aerated soils are red, yellow, or brown due to the presence of ferric iron compounds; gray soils contain ferrous iron compounds. Dark soils contain decaying organic matter. Soil analysis in corrosion studies involves only substances present as water-soluble compounds, including base formers such as sodium, potassium, calcium, and magnesium, and acid formers such as carbonate, bicarbonate, chloride, nitrate, and sulfate.

Aeration and water-retention characteristics are the chief physical attributes of soil. Coarse soils (sands and gravels) that have good drainage and ample aeration corrode steel at a rate approaching that of the local atmosphere. Clay and silt soils are characterized by fine texture, high water retention, poor aeration, and poor drainage, all of which increase corrosion rates for steel. The most severe corrosion usually takes place at low elevations in poorly drained soils where there is minimal aeration.

Differential Aeration. Corrosion by differential aeration can result from various conditions. For example, when a pipe passes through two different soils that differ in oxygen permeability, a galvanic current will flow from the more poorly aerated (anodic) surface of the pipe through the soil to the better aerated (cathodic) surface. If the two surface conditions are widely separated, these galvanic currents, known as long-line currents, can be detected and used to locate the anodic areas.

Dissolved Salts. The most corrosive soils are those that contain large concentrations of soluble salts. Because of the presence of salts, such soils have relatively high electrical conductivities (or low electrical resistivities). The least-corrosive soils have low concentrations of soluble salts and high resistivities. Resistivity measurements can be obtained readily and provide as much information on corrosion characteristics as do measurements of any other single soil property. Consequently, resistivity is the property most often used to approximate the aggressiveness of a soil. Observations of soil drainage, and/or measurements of pH supplement resistivity measurements. The following table lists the general relationship that exists between soil resistivity and corrosion of ferrous metals; however, because of other factors this relationship may not always be valid.

Soil restivity, $\Omega \cdot$ m	Classification
<7	**Very corrosive**
7-20	**Corrosive**
20-50	**Moderately corrosive**
>50	**Mildly corrosive to noncorrosive**

Bacterial Action

Bacterial action is another factor that influences underground corrosion. Of the various bacteria in soils, the anaerobic sulfate-reducing bacteria are of greatest concern. These bacteria can act as depolarizers for the cathodic reaction $H_2O + e^- \rightarrow H^0 + OH^-$, and thereby allow corrosion to proceed in oxygen-free soils. It should be noted that the conditions favorable to the activity of these bacteria (soluble sulfate) would be detected by the resistivity measurements mentioned above.

Preventive Measures

Although other methods of corrosion control, such as the use of protective coatings, are often used to combat soil corrosion of steel, the cathodic protection method is regarded as the most economical and effective method available. Cathodic protection offers two important advantages. First, it can be retrofitted to existing structures, usually at a small fraction of the cost of replacing the structure and without major disruption of the facility or service; and second, the effectiveness of the cathodic protection in arresting corrosion can be measured by a simple, nondestructive electrical measurement.

Corrosion in Concrete

THE CORROSION PROCESS in concrete is such that it tends to create conditions that increase the rate of attack. This phenomenon is related to the fact that the various corrosion products of iron and steel have a larger specific volume than the steel itself. The increase in volume of the corrosion products causes stresses that can lead to cracks in the concrete. These cracks allow easier access for the attacking medium and therefore more rapid attack. When the cracks are open to the exterior, corrosion products can be washed out and often lead to cosmetically objectionable stains. Of greater concern is the case of prestressed concrete. In this material, the corrosion process can lead to loss of structural strength and eventual failure.

The presence of chloride ions is one of the principal causes of steel corrosion in concrete. These result from airborne contaminants or deicing salts. Various attempts at reducing or eliminating the corrosion problem have focused on protective coatings for the steel members (galvanizing, painting, and so on), decreasing the concrete permeability, increasing the depth of concrete cover, or eliminating the chloride ion through the use of sealants, and so on. Although many of these approaches have shown some degree of success, the application of cathodic protection has been the most successful in arresting corrosion.

There does not appear to be any significant body of data relating the severity of corrosion to the composition of the steel reinforcing member. It is likely that alloying could reduce the overall rate of attack, but whether the reduction would be significant in light of the added cost is problematic. Some HSLA concrete-reinforcing bars covered in ASTM A 706 are used for special applications.

Corrosion in Fresh Water

FRESH WATER includes all nonsaline natural waters, polluted or unpolluted, found in inland bodies such as streams, rivers, ponds, and lakes. In addition to nonsaline natural waters, which originate as precipitation such as rain or snow, fresh water includes well water, treated potable water, and various process waters that can or cannot be treated and can or cannot contain higher levels of contaminants than the natural waters from which they were derived. Data on the useful life of mild steel in contact with fresh water are incomplete without information on: (a) mineral quality of the water, (b) acidity, (c) presence or absence of dissolved oxygen, (d) velocity of flow, (e) temperature, and (f) environmental conditions such as nonuniformity of a corrosion-product deposit, contact with copper-bearing metals, and the existence of crevices, all of which can lead to severe localized corrosion.

Effect of Dissolved Gases

Of all the characteristics of water that influence the rate of corrosion, dissolved gases are probably the most important.

Oxygen. The rate at which oxygen reaches a metal surface controls the rate of corrosion and can determine whether aerobic or anaerobic corrosion results. In addition, oxygen accelerates the action of carbon dioxide, hydrogen sulfide, and other dissolved gases and solids.

Carbon dioxide is only about one-tenth as corrosive as oxygen, and in natural waters the carbon dioxide concentration is important only as it affects the solubility and precipitation of calcium carbonate.

Hydrogen sulfide can cause rapid attack of steel, even in the absence of oxygen; it also produces severe graphitic corrosion of cast iron. The anaerobic corrosion products are sulfur and ferrous sulfide, both of which are cathodic to iron and tend to cause severe pitting. Most of the corrosion problems due to hydrogen sulfide arise when this chemical is produced by bacteria.

Effect of pH

There is little difference in the corrosion rate of steel in natural waters having pH values between 4.5 and 9.5. This has been confirmed in both tap water and distilled water. In this range of pH, the corrosion products maintain a pH of 9.5 next to the steel surface, regardless of the pH of the solution. At a pH of 4 or below, hydrogen evolution begins and corrosion increases rapidly (Fig. 2).

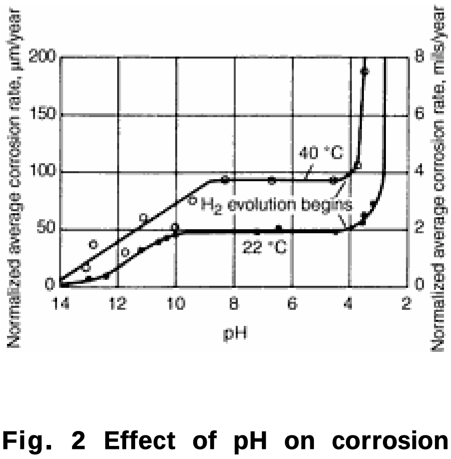


Fig. 2 Effect of pH on corrosion of steel in aerated water. Corrosion rates are normalized to a solution containing 1 mL O_2 per liter of water. To estimate corrosion rates at other concentration, multiply values derived from this graph by the oxygen concentration in mL/L.

Effect of Dissolved Salts

Most salts dissolved in water tend to decrease the solubility of both oxygen and ferrous hydroxide. Therefore, rates of corrosion in concentrated salt solutions are usually less than those in dilute salt solutions. Some salts also tend to buffer the pH value, which can overcome a tendency toward acidic corrosion. On the other hand, most dissolved salts become ionized and increase the conductivity of water which, in turn, tends to localize corrosion, thus leading to severe pitting, The increased conductivity permits cathodic areas to become larger and causes anode and cathode reaction products to combine in the water instead of at the corroding surface. Cations stimulate corrosion in the following order (magnesium ions having the least effect and ferric ions the greatest): magnesium, cadmium, manganese, calcium, strontium, barium, lithium, sodium, potassium, ammonium, trivalent chromium, and trivalent iron (ferric).

Ammonium salts and salts of trivalent elements such as chromium and iron greatly stimulate corrosion because they hydrolyze, creating acidic conditions. Corrosion then occurs by hydrogen evolution as well as by oxygen depolarization. Ammonium chloride is particularly active, even at concentrations as low as 10 ppm.

Copper and Mercury Irons. Certain soluble ions, especially copper and mercury, are capable of undergoing a reaction termed mutual replacement, in which the dissolved ions (which are more noble than iron) deposit on an iron or steel surface and an equal number of iron atoms go into solution. Mutual replacement can take place in the absence of oxygen, and there is no known inhibitor that can prevent this reaction.

Alkali Metal Salts. When salts of lithium, sodium, or potassium are added to aerated water, the corrosion rate varies with concentration. At low concentrations, addition of an alkali metal salt increases the corrosion rate; at higher concentrations, the corrosion rate reaches a maximum and then decreases with increasing concentration, as shown in Fig. 3.

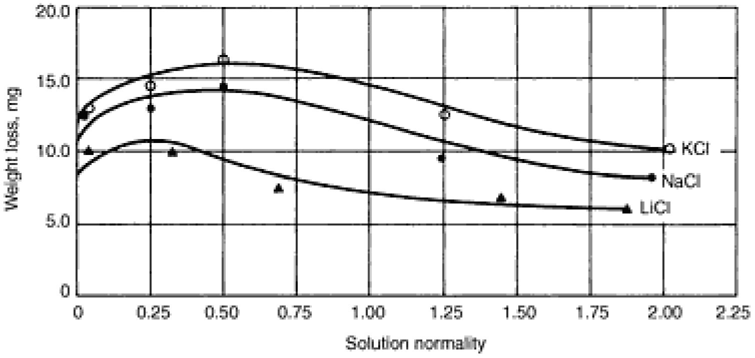


Fig. 3 Effect of alkali metal salt concentration on corrosion of steel at 35 °C (95 °F)

Corrosion in Potable Water Systems

Steel pipe is not used for domestic potable water. Other steel containers seldom are used for household or industrial water or for water distribution systems without protective coatings of zinc, cement, enamel, paint, coal tar, or a coal-tar-base product. Such coatings are necessary not only to reduce corrosion but also to avoid red water. Steels exposed to water at gaps (holidays) in coatings or at joints will not resist aggressive water but will remain unattacked in nonaggressive water, in water that has been treated with the proper inhibitor, or when placed under cathodic protection.

Corrosion in Natural Waters

Steel is used for structures, pilings, and water-intake piping that are completely or partly submerged in various natural waters. In virtually all applications, the corrosion rate is influenced not only by the prevailing oxygen content of the natural water, but also by the presence of minerals or industrial pollutants, or both. The prevailing pH and degree of movement around an exposed steel structure (producing turbulent flow, laminar flow, or stagnation) also affect the corrosion rate. Frequently, it is impossible to predict useful life with any reasonable certainty without conducting corrosion tests at the site.

Corrosion in Seawater

SEAWATER is a relatively uniform saline solution consisting predominantly of sodium and magnesium chlorides dissolved in water. Although many other soluble minerals are present in very small quantities, both the individual and cumulative effects of these minerals are so greatly overshadowed by the effect of the dominant chlorides that seawater can be considered equivalent to a 0.5*N* sodium chloride solution. At this concentration, a sodium chloride solution is at a peak in corrosivity, acting more aggressively toward steel than at either higher or lower concentrations. Factors other than chloride concentration that affect corrosion in seawater include oxygen concentration, biofouling, water velocity, and water temperature. These factors are discussed later in this article.

The corrosion rate most commonly cited for carbon steel immersed in seawater is 5 mils/year (130 μm/year). This rate my be considered linear with time up to about eight years. After about eight years, the corrosion rate decreases to a steady, but slower, rate. In one instance, examination of steel H-piles exposed to unpolluted seawater in the Santa Barbara Channel indicated that the loss due to corrosion is about 1 mm (40 mils) over a 20 year interval, or a rate of about 50 μm/year (2 mils/year), which can be reduced to about 25 μm/year (1 mil/year) thereafter.

Corrosion in brackish waters, such as is found in bays and estuaries, parallels corrosion in seawater to a certain extent. However, because of the periodic reversal in flow typical of many brackish waters and because of certain other characteristics, the pattern of corrosion in brackish waters differs from the pattern in ordinary seawater.

Effect of Mill Scale

Corrosion rates around the world are somewhat similar, regardless of whether they are measured in terms of weight loss or of maximum pit depth. However, in almost all instances, maximum pit depth is much greater in carbon steel specimens covered with mill scale than in specimens that are free of mill scale, as shown in Table 3. Mill scale is very cathodic to bare steel.

Table 3 Corrosion of mill-scaled surface of carbon steel immersed in seawater versus corrosion of scale-free surface

Location	**Pickled surface**				Mill-scaled surface			
	Corrosion loss		**Max pit depth**		**Corrosion loss**		Max pit depth	
	μm/yr	**mils/yr**	**mm**	**mils**	**μm/yr**	**mils/hr**	**mm**	mils
Halifax, Nova Scotia	120	4.8	1.9	75	110	4.3	1.7	**68**
Auckland, New Zealand	75	3.0	1.1	43	85	3.3	3.7	**147**
Plymouth, England	60	2.4	1.65	65	60	2.4	4.0	**156**
Colombo, Sri Lanka	**90**	**3.6**	**1.6**	**64**	**100**	**3.9**	**6.1**	**240**

Effect of Oxygen Concentration

It is the cathodic depolarizing effect of oxygen that permits most corrosion reactions to proceed. In practice, the various natural forms of inhibition that prevent access of oxygen to a metal surface reduce the corrosion rate and often stifle corrosion completely.

In one instance, the effects of such parameters of the deep-sea environment as oxygen concentration, salinity, temperature, and pH were investigated. Some of the data from that study are given in Table 4. The corrosion rate for steel was determined to be a linear function of dissolved oxygen content.

Table 4 Corrosion rates of carbon steel for near-surface and deep-sea immersion

Immersion depth		**Temperature, °C**	**Oxygen concentration, ppm**	**Immersion time, days**	Corrosion rate	
m	**ft**				**μm/yr**	mils/yr
Near-surface site[a]						
. . .	. . .	5-30	5-10	365	130	**5.0**
Deep-sea site[b]						
715	2340	7.2	0.6	197	43	**1.7**
1615	5300	2.5	1.8	1604	23	**0.9**
1720	5640	2.8	1.2	123	50	**2.0**
		2.3	2.1	751	20	**0.8**
2065	**6780**	**2.7**	**1.7**	**403**	**58**	**2.3**

(a) Wrightsville Beach, NC.

(b) Pacific Ocean.

Galvanic Corrosion

Galvanic corrosion in seawater is a matter of concern because the corroding medium has a fairly high conductivity. A practical version of the galvanic relationship of metals in seawater is shown in Table 5. Service conditions can differ considerably because of solution composition, solute concentration, agitation, aeration, temperature, and purity of the metals, as well as corrosion-product formation and biological growth, each of which can result in a different galvanic series.

Table 5 Galvanic series in seawater

1.	**Magnesium (most active)**
2.	**Magnesium alloys**
3.	**Zinc.**
4.	**Aluminum 100**
5.	**Cadmium**
6.	**Aluminum 2017**
7.	**Steel (plain)**
8.	**Cast iron**
9.	**Chromium iron (active)**
10.	**Nickel cast iron**
11.	**304 stainless (active)**
12.	**316 stainless (active)**
13.	**Hastelloy C**
14.	**Lead-tin solders**
15.	**Lead**
16.	**Tin**
17.	**Nickel (active)**
18.	**Inconel (active)**
19.	**Hastelloy B**

20. Brasses
21. Copper
22. Bronzes
23. Copper-nickel alloys
24. Titanium
25. Monel
26. Silver solder
27. Nickel (passive)
28. Inconel (passive)
29. Chromium iron (passive)
30. 304 stainless (passive)
31. 316 stainless (passive)
32. Silver
33. Graphite (least active)

Basic Corrosion Rates in Seawater

Carbon steel and many of the low-alloy steels are frequently cited as having short-term corrosion rates of about 130 μm/year (5 mils/year) when completely immersed in seawater. The long-term corrosion rates of these steels (after immersion for five to ten years) are somewhat lower.

It is generally conceded that steelmaking practice has no effect on corrosion in seawater; there is no substantial difference in behavior between rimmed and killed steel. Likewise, alloying with small amounts of either copper or chromium has no effect on corrosion. In one investigation, for example, seven different open-hearth steels, six copper-bearing steels, and several low-chromium copper-bearing steels were immersed in seawater for 203 days; the corrosion rates for all these steels were in the relatively narrow range of 135 to 150 μm/year (5.4 to 5.8 mils/year).

Effect of Velocity. Increasing the velocity of seawater generally increases the rate of corrosion. For instance, one study showed that the corrosion rate in stagnant seawater was the same for both carbon steel and copper-bearing steel--about 70 μm/year (2.8 mils/year)--for immersion periods of 5 to 10 years. In seawater flowing at low velocity, the corrosion rate for carbon steel was about 95 μm/year (3.8 mils/year), but at higher velocity the corrosion rate was 380 μm/year (15 mils/year). The corrosion rate for copper-bearing steel in high-velocity seawater was only about 120 μm/year (5.5 mils/year), which indicates a possible benefit from alloying with small amounts of copper. Most investigators consider the effect of velocity on corrosion rates to be an erosion effect, whereby corrosion products are continually removed from the surface as they form, which reduces their effectiveness in stifling further corrosion.

Pitting. Where pitting is a serious consideration, steels containing up to 3% Ni or 3% Cr may be used. Both nickel steels and chromium steels pit at about half the rate of carbon steel. For instance, in one six year immersion test, a 2% Ni steel pitted to an average depth of about 2 mm (80 mils), compared to a depth of 5 mm (200 mils) for carbon steel. Increasing the amount of chromium above 3% changes the mode of corrosion to an increasingly more localized attack with deeper pits. For instance, a 3% Cr steel typically exhibits pitting rates of about 0.2 mm/year (8 mils), compared to about 0.9 mm/year (37 mils) for a 13% Cr steel and a 1.75 mm/year (69 mils/year) for a 17% Cr steel.

Corrosion in Tropical Waters. The higher temperature of seawater in tropical climates than in temperate or arctic climates results in higher rates of corrosion. Results of a systematic study conducted in both fresh water and seawater in a tropical climate are given in Table 6; in this climate, as in more temperate climates, the average corrosion rates for both carbon and HSLA steels decrease with time in both fresh and salt water. Furthermore, the average depth of the 20 deepest pits is about the same for both carbon and copper-bearing steels, higher after long-term exposure for Ni steels, and slightly lower for long-term exposure only for 5% Cr steel. Besides the results given in Table 6, a 3% Cr steel and several HSLA steels containing various amounts of Ni, Cr, P, Cu, and Si were subjected to the same conditions and gave about the same results, as those reported for similar steels in Table 6.

Table 6 Typical corrosion rates in tropical waters

Material	**Average penetration rate**						Average depth of 20 deepest pits					
	1 yr		**8 yr**		**16 yr**		**1 yr**		**8 yr**		16 yr	
	μm/yr	**mils/yr**	**μm/yr**	**mils/yr**	**μm/yr**	**mils/yr**	**μm/yr**	**mils/yr**	**μm/yr**	**mils/yr**	**μm/yr**	mils/yr
Fresh water(a)												
Carbon steel(b)	195	7.7	65	2.58	45	1.75	510	20	1470	58	1830	**72**
0.30 Cu steel	200	7.9	75	2.9	45	1.8	560	22	1630	64	1630	**64**
Seawater(c)												
Carbon steel(b)	150	5.9	80	3.2	75	2.9	1040	41	1680	66	2290	**90**
0.3 Cu steel	150	5.9	90	3.5	80	3.1	915	36	1600	63	160	**85**
2 Ni steel	190	7.4	100	4	85	3.3	840	33	2390	94	(d)	**(d)**
5 Ni steel	160	6.3	100	4	85	3.3	735	29	2970	117	(d)	**(d)**
5 Cr steel	**70**	**2.7**	**100**	**4**	**85**	**3.5**	**685**	**27**	**1600**	**63**	**1750**	**69**

(a) Gatun Lake, CZ.

(b) Pickled.

(c) Pacific Ocean, near Panama Canal Zone.

(d) Specimen corroded through.

Preventive Measures

The use of organic coatings in conjunction with cathodic protection offers the most economical and effective method of corrosion prevention in seawater. Offshore oil rigs, pipelines, and other underwater equipment make use of this combination. The less porous the coating, the less current needed for cathodic protection and the more economical the system. Aluminum anodes, with their high current efficiency, are most often used in seawater. However, zinc anodes also have been used extensively in seawater applications, while magnesium anodes have been used less extensively. The slight advantage of low-alloy steels over carbon steels usually is lost in the final economic analysis of corrosion prevention.

Inhibitors are sometimes used in seawater cooling equipment. Wherever possible, all equipment in contact with seawater should be designed without galvanic couples.

Stress-Corrosion Cracking of Steels

STRESS CORROSION CRACKING (SCC) is slow, environmentally induced crack propagation in engineering materials that results from the combined interaction of mechanical stress and corrosion reactions. Generally. steels with lower strengths are susceptible to SCC only upon exposure to a small number of specific environments, such as the hot caustic solutions encountered in steam boilers. hot nitrate solutions, anhydrous ammonia, and hot carbonate-bicarbonate solutions.

For steels with yield strengths greater than about 690 MPa (100 ksi)--such as quenched-and-tempered alloy steels, hot-work die steels, maraging steels, and martensitic and precipitation-hardenable stainless steels--the environments that cause SCC are not specific. In many alloy systems, the phenomena of SCC and hydrogen embrittlement cracking are indistinguishable. This is particularly the case in environments that contain sulfides or other promoters of hydrogen entry.

Environments of major concern are natural waters--for example, rainwater, seawater, and atmosphere moisture. Any of these environments may become contaminated, which significantly increases the likelihood of SCC. Contamination with hydrogen sulfide is particularly serious: consequently, the presence of hydrogen sulfide in high concentrations in salt water associated with certain deep oil wells (termed sour wells) places an upper limit of approximately 620 MPa (90 ksi) on the yield strength that can be tolerated in stressed steel in such environments without cracking.

Protection of Steel from Corrosion

CORROSION PROTECTION is often an essential consideration in selection of carbon or alloy steel for a given structural application. Corrosion can reduce the load-carrying capacity of a component either by generally reducing its size (cross section) or by pitting, which not only reduces the effective cross section in the pitted region, but also introduces stress raisers that may initiate cracks. Obviously, any measure that reduces or eliminates corrosion will extend the life of a component and increase its reliability (Table 7).

Table 7 Guide to corrosion prevention for carbon steels in various environments

Preventive method	**Atmosphere**	**Soil**	**Fresh water**	**Seawater**	**Steam systems**	Acids and pickling baths
Metal coatings: electroplating, galvanizing, thermal spraying	Galvanizing very effective; plating with other metals used for both decorative appearance and corrosion protection	Not recommended	Galvanizing used in potable water	Not recommended	Not recommended	**Not recommended**
Painting: chemical treatment, priming and painting	Most economical and effective corrosion prevention	Seldom used	Fairly effective	Special paint systems used	Not recommended	**Not recommended**
Cathodic protection	Not recommended	Most economical and effective method, especially with organic coatings	Fairly effective with organic coatings	Very effective	Not recommended	**Effective under special conditions**

		other than paint				
Inhibitors: liquid and vapor	Not recommended	Not recommended	Effective in some applications, especially cooling waters	Fairly effective in some applications	Very effective	**Very effective**
Alloying additions to steel	Very effective, especially copper-bearing and HSLA steels	Not effective	Not effective	Only effective with much alloying	Chromium-molybdenum steels are very effective	**Only effective with much alloying**
Removal of oxygen from environment	Not recommended	Not recommended	Seldom used	Very effective, especially in desalination and hot seawater	Very effective	**Not recommended**
Removal of more noble metals; elimination of galvanic couples	Usually not necessary	Fairly effective	Effective	Necessary	Advisable	**Not effective**
Organic coatings other than paint	**Seldom used to replace painting**	**Used to advantage with cathodic protection**	**Fairly effective with cathodic protection**	**Used to advantage with cathodic protection**	**Not recommended**	**Have been used**

Overall economics, environmental conditions, degree of protection needed for the projected life of the part, consequences of unexpected service failure, and importance of appearance are the chief factors that determine not only whether a steel part needs to be protected against corrosion, but the most effective and economic method of achieving that protection as well. Protection against corrosion can be done by (a) providing an impervious barrier between the steel and the corroding medium, (b) introducing a substance that inhibits the chemical action, or (c) inducing galvanic activity that counteracts the galvanic activity involved in corrosion.

Coatings

The types of coatings available seem endless, varying from simply oiling the surface for low-cost temporary protection to electroplating with a multilayer copper-nickel-chromium coating to obtain a high-gloss metallic appearance and superior corrosion protection. For economic reasons, the desired degree of protection must be determined before a coating is selected.

Temporary protection during storage or shipment usually can be done effectively by coating the steel with mineral oil, solvents combined with inhibitors and film formers, emulsions of petroleum-based coatings, or water plus waxes. These coatings are applied (a) after acid pickling to remove mill scale or (b) between coating sequences and are not expected to give long-term corrosion protection.

Cleaning is the most important prerequisite for any coating process, Any oxides on a steel surface must be removed by acid pickling or sand blasting. Degreasing is necessary after oxide removal or when the steel has been given a temporary coating. Degreasing can be accomplished by alkaline cleaning, vapor degreasing, or emulsion cleaning.

Hot dip coating processes are particularly well suited for applying coatings of aluminum, lead, tin, zinc, and some of their alloys. Hot dipping consists of immersing the steel in a bath of molten metal that usually is covered with a layer of molten flux. Zinc coating (galvanizing) protects steel galvanically because the zinc is anodic to the steel base metal and therefore corrodes preferentially in most environments.

Electroplating is perhaps the most expensive of all processes for coating steel. Electrodeposits, therefore, are used when appearance, solderability, or some other requirement demands a metal coating. If only corrosion protection is needed, many nonmetallic coatings will give better protection at lower cost. All conventional electroplates can be applied to steel.

Thermal spray coatings provide effective long-term corrosion protection for steels in a wide range of corrosive environments. They are applied by one of several processes, including wire flame spraying, powder flame spraying, and electric arc spraying. Zinc, aluminum, and zinc-aluminum alloys are the most common coating materials applied by thermal spray techniques.

Conversion coatings offer only mild corrosion protection to steel if not covered with another system but become very protective when used with paints. Phosphate coatings and chromate conversion coatings are widely used as paint bases on both uncoated and galvanized steel.

Thin organic coatings (paints) are used more often for corrosion protection than any of the other coatings because the cost is low for the degree of protection afforded. A good paint system includes proper cleaning, a conversion coating, a primer, and a compatible top coat. Application of the various coats can be accomplished by spraying, dipping, flow coating, roller coating, or electrophoretic deposition.

Inhibitors

An inhibitor is a chemical substance or combination of substances that, when present in the environment, prevents or reduces corrosion without significant reaction with the components of the environment. Inhibitors find their major uses in acid-pickling solutions, acidic service environments, steam systems, and neutral and near-neutral aqueous solutions. Inhibitors may be organic or inorganic compounds, and they are usually dissolved in aqueous environments. Inhibitors have been added to chemical conversion treatment baths and to paint primers. A few vapor-phase inhibitors are used in confined atmospheres (for example, packaging applications).

Basic Metallurgy of Cast Iron

Introduction

CAST IRON, like the term steel, identifies a large family of ferrous alloys. Cast irons primarily are iron alloys that contain more than 2% carbon and from 1 to 3% silicon. Wide variations in properties can be achieved by varying the balance between carbon and silicon, by alloying with various metallic elements, and by varying melting, casting, and heat treating practices.

The five types of commercial cast iron are gray, ductile, malleable, compacted graphite, and white iron. With the exception of a white cast iron, all cast irons have in common a microstructure that consists of graphite phase in a matrix that may be ferritic, pearlitic, bainitic, tempered martensitic, or combinations thereof. The four types of graphitic cast irons are roughly classified according to the morphology of the graphite phase. Gray iron has flake-shaped graphite, ductile iron has nodular or spherically shaped graphite, compacted graphite iron (also called vermicular graphite iron) is intermediate between these two, and malleable iron has irregularly shaped globular or "popcorn-shaped" graphite that is formed during tempering of white cast iron. Table 1 shows the correspondence between commercial and microstructural classification, as well as final processing stage in obtaining common cast irons.

Table 1 Classification of cast irons by commercial designation, microstructure, and fracture

Commercial designation	**Carbon-rich phase**	**Matrix**(a)	**Fracture**	Final structure after
Gray iron	Lamellar graphite	P	Gray	**Solidification**
Ductile iron	Spheroidal graphite	F, P, A	Silver-gray	**Solidification or heat treatment**
Compacted graphite iron	Compacted (vermicular) graphite	F, P	Gray	**Solidification**
White iron	Fe_3C	P, M	White	**Solidification and heat treatment**(b)
Mottled iron	Lamellar Gr + Fe_3C	P	Mottled	**Solidification**
Malleable iron	Temper graphite	F, P	Silver-gray	**Heat treatment**
Austempered ductile iron	**Spheroidal graphite**	**At**	**Silver-gray**	**Heat treatment**

(a) F, ferrite; P, pearlite; A, austenite; M, martensite; At, austempered (bainite).

(b) White irons are not usually heat treated, except for stress relief and to continue austenite transformation.

White cast irons, so named because of the characteristically white fracture surfaces, do not have any graphite in the microstructures. Instead the carbon is present in the form of carbides, chiefly of the types Fe_3C and Cr_7C_3. Often, complex carbides are also present, such as $(Fe,Cr)_3C$ from additions of 3 to 5% Ni and 1.5 to 2.5% Cr, $(Cr,Fe)_7C_3$ from additions of 11 to 35% Cr, or those containing other carbide-forming elements.

Cast irons may also be classified as either unalloyed cast irons or alloy cast irons. Unalloyed cast irons are essentially iron-carbon-silicon alloys containing small amounts of manganese, phosphorus, and sulfur. The range of composition for typical unalloyed cast irons is given in Table 2. Figure 1 shows the range of carbon and silicon for common cast irons as compared with steel.

Table 2 Range of compositions for typical unalloyed common cast irons

Type of iron	Composition, %				
	C	**Si**	**Mn**	**P**	S
Gray	2.5-4.0	1.0-3.0	0.2-1.0	0.002-1.0	**0.02-0.25**
Compacted graphite	2.5-4.0	1.0-3.0	0.2-1.0	0.01-0.1	**0.01-0.03**
Ductile	3.0-4.0	1.8-2.8	0.1-1.0	0.01-0.1	**0.01-0.03**
White	1.8-3.6	0.5-1.9	0.25-0.8	0.06-0.2	**0.06-0.2**
Malleable	**2.2-2.9**	**0.9-1.9**	**0.15-1.2**	**0.02-0.2**	**0.02-0.2**

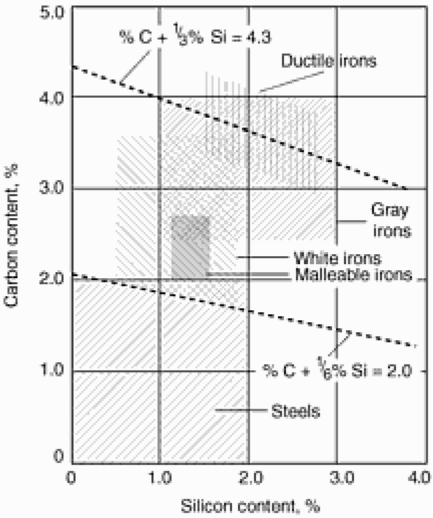


Fig. 1 Approximate ranges of carbon and silicon for steel and various cast irons

The Iron-Iron Carbide-Silicon System

A section through the ternary Fe-Fe_3C-Si diagram at 2% Si (which approximates the silicon contents of many cast irons) provides a convenient reference for discussing the metallurgy of cast iron. The diagram in Fig. 2 resembles the binary Fe-Fe_3C diagram but exhibits important differences characteristic of ternary systems. Eutectic and eutectoid temperatures change from single values in the Fe-Fe_3C system to temperature ranges in the Fe-Fe_3C-Si system; the eutectic and eutectoid points shift to lower carbon contents.

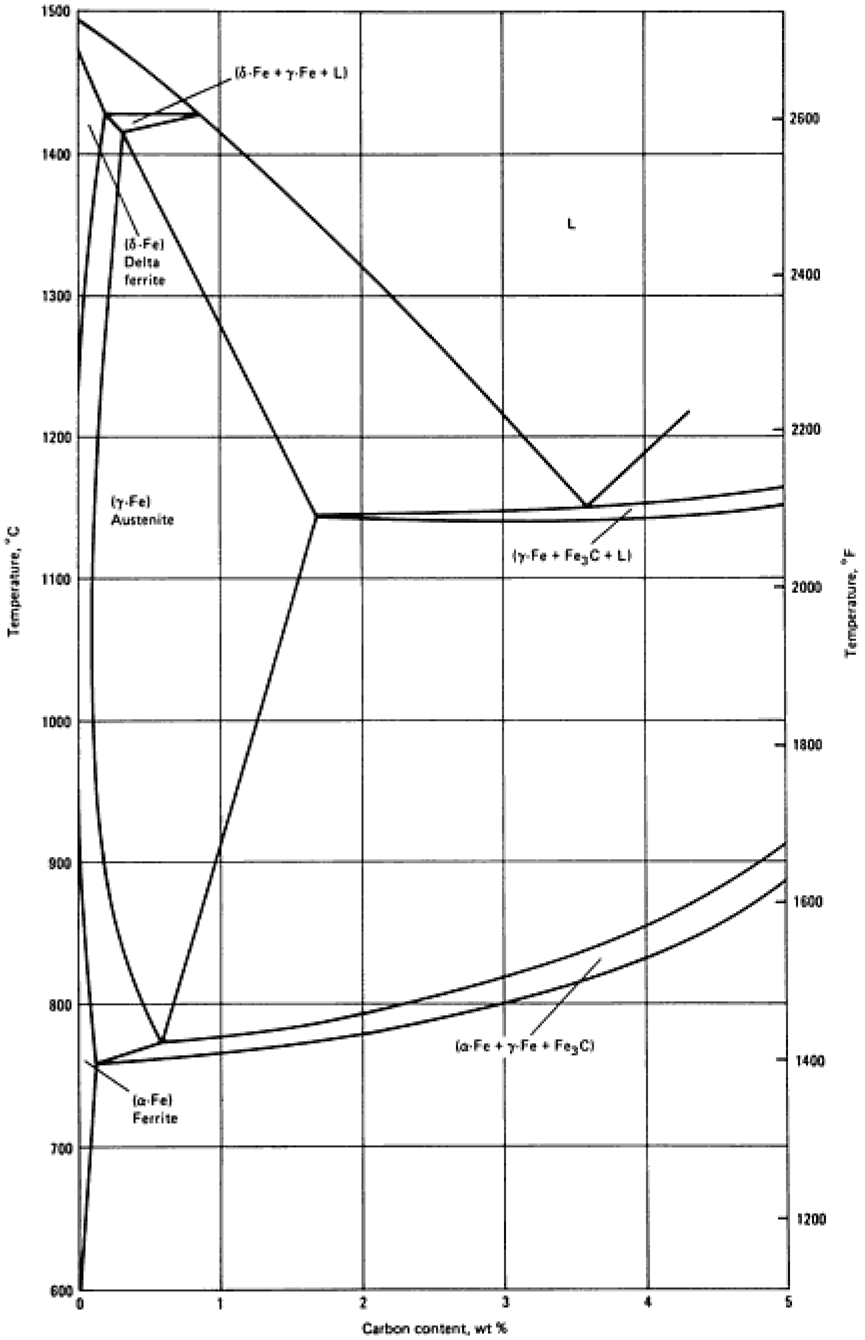


Fig. 2 Section through the Fe-Fe_3C-Si ternary equilibrium diagram at 2% Si

Figure 2 represents the metastable equilibrium between iron and iron carbide (cementite), a metastable system. The silicon that is present remains in solid solution in the iron, in both ferrite and austenite, and so does not affect the composition of the carbide phase but only the conditions and the kinetics of the carbide formation on cooling. The designations α, γ, and Fe_3C, therefore, are used in the ternary system to identify the same phases that occur in the Fe-Fe_3C binary system. Some of the silicon may precipitate along with the carbide, but it cannot be distinguished as a different phase. The solidification of certain compositions does not occur in the metastable system, but rather in the stable system, where the products are iron and graphite rather than iron and carbide. These compositions encompass the gray, ductile, and compacted graphite cast irons.

If the section through the ternary diagram at 2% Si is to be used in tracing the phase changes that occur, its use can be justified only on the assumption that silicon concentration remains at 2% in all parts of the alloy under all conditions. This obviously is not strictly true, but there is little evidence that silicon segregates to any marked degree in cast iron.

Carbon Equivalence

Both carbon and silicon influence the nature of iron castings, so it is necessary to develop an approximation of their impact on solidification. This has been accomplished through development of the concept of carbon equivalence, *CE*. Using this approach, carbon equivalence is calculated as:

$$CE = \%C + \frac{\%Si}{3}$$

or more precisely, taking phosphorus into consideration:

$$CE = \%C + \frac{\%Si + \%P}{3}$$

Comparison of *CE* with the eutectic composition in the Fe-C system (4.3% C) will indicate whether a cast iron will behave as a hypoeutectic or hypereutectic alloy during solidification. When *CE* is near the eutectic value, the liquid state persists to a relatively low temperature and solidification takes place over a small temperature range. The latter characteristic can be important in promoting uniformity of properties within a given casting.

In hypereutectic irons (*CE* greater than about 4.3%), there is a tendency for kish graphite--proeutectic graphite that forms and floats free in the molten iron--to precipitate on solidification under normal cooling conditions. In hypoeutectic irons, the lower the *CE*, the greater the tendency for white or mottled iron to form on solidification.

Characteristics of Cast Irons

White Cast Iron. White iron is formed when the carbon in solution in the molten iron does not form graphite on solidification but remains combined with the iron, often in the form of massive carbides. White irons are hard and brittle and produce white, crystalline fracture surfaces.

White cast irons have high compressive strength and good retention of strength and hardness at elevated temperature, but they are most often used for their excellent resistance to wear and abrasion. The massive carbides in the microstructure are chiefly responsible for these properties.

Gray Cast Iron. When the composition of the iron and the cooling rate at solidification are suitable, a substantial portion of the carbon content separates out of the liquid to form flakes of graphite. When a piece of the solidified alloy is broken, the fracture path follows the graphite flakes, and the fracture surfaces appear gray because of the predominance of exposed graphite.

Gray cast iron has several unique properties that are derived from the existence of flake graphite in the microstructure. Gray iron can be machined easily at hardnesses conducive to good wear resistance. It resists galling under boundary-lubrication conditions (conditions wherein the flow of lubricant is insufficient to maintain a full fluid film). It has outstanding properties for applications involving vibrational damping or moderate thermal shock.

Ductile Cast Iron. Ductile iron, which is also known as nodular iron or spheroidal graphite cast iron, is very similar to gray iron in composition, but during casting of ductile iron the graphite is caused to nucleate as spherical particles, or spherulites, rather than as flakes. This is accomplished through the addition of a very small but definite amount of magnesium and/or cerium to the molten iron in a process step called nodulizing.

Ductile iron is produced from the same types of raw material as gray iron, but usually requires slightly higher purity, especially in regard to sulfur. Casting properties of ductile iron, such as fluidity, are comparable to those of gray iron.

The chief advantage of ductile iron over gray iron is its combination of high strength and ductility--up to 18% minimum elongation for ferritic ductile iron with a tensile strength of 415 MPa (60 ksi) as opposed to only about 0.6% elongation for a gray iron of comparable strength. Martensitic ductile irons with tensile strengths of about 830 MPa (120 ksi) exhibit at least 2% elongation, and the newer austempered ductile irons exhibit in excess of 5% elongation at even higher tensile strengths (1000 MPa, or 145 ksi).

For most applications, some deviation from true spherical shape can be tolerated without unacceptable loss of properties. However, the quasi-flake and crab form (see Table 3) are unacceptable for most applications.

Table 3 Summary and description of ASTM and equivalent ISO classification of graphite shapes in cast iron

ASTM type[(a)]	**Equivalent ISO form**[(b)]	Description
I	VI	**Nodular (spheroidal) graphite**
II	VI	**Nodular (spheroidal) graphite, imperfectly formed**
III	IV	**Aggregate, or temper carbon**
IV	III	**Quasi-flake graphite**
V	II	**Crab-form graphite**
VI	V	**Irregular or "open" type nodules**
VII[(c)]	**I**	**Flake graphite**

(a) As defined in ASTM A 247.

(b) As defined in ISO/R 945-1969 (E).

(c) Divided into five subtypes; uniform flakes; rosette grouping; superimposed flake size; interdendritic, random orientation; and interdendritic, preferred orientation

Compacted graphite (CG) cast iron, also known as vermicular graphite cast iron, is characterized by graphite that is interconnected within eutectic cells as is the flake graphite in gray iron. Compared with the graphite in gray iron, however, the graphite in CG iron is coarser and more rounded, similar in metallographic appearance to ASTM type IV, quasi-flake graphite (Table 3). The structure can be considered intermediate between those of gray iron and ductile iron. Individual properties can also be considered intermediate between those of gray and ductile irons, but the unique combinations of properties obtainable in CG irons make them superior to either gray or ductile iron in applications such as disc-brake rotors and diesel-engine heads.

Compacted graphite cast iron can be obtained by very carefully controlling the amount of magnesium added as an inoculant in a process very similar to the process used to make ductile iron. Unfortunately, either undertreatment, resulting in a gray iron structure, or overtreatment, resulting in a ductile iron structure, can occur if the ideal quantity of magnesium is missed by as little as 50 ppm. Current commercial production of CG iron is accomplished by inoculation with magnesium to give a residual content of 50 to 600 ppm in the presence of 0.15 to 0.5% titanium and 10 to 150 ppm of rare earths, such as cerium. In effect, the process is one in which the nodulizing reaction due to the addition of magnesium is poisoned by the presence of a controlled amount of titanium, and in which cerium is added to eliminate a need to control sulfur at a low concentration.

Malleable cast iron encompasses yet another form of graphite called temper carbon. This form of graphite is produced by the heat treatment of white cast iron, which does not contain graphite, but does contain a high percentage of cementite. When a white cast iron is heated for an extended period of time (about 60 h) at a temperature of 960 °C (1760 °F), the cementite decomposes into austenite and graphite. By slow cooling from 960 °C (1760 °F), the austenite transforms into ferrite or pearlite, depending on the cooling rate and the diffusion rate of carbon. The ductility and toughness of malleable iron falls between that of ductile cast iron and gray cast iron. Because white iron can only be produced in cast sections up to about 100 mm (4 in.) thick, malleable iron is limited in section size. In recent years, malleable irons have been replaced by the more economically processed ductile irons for many applications.

Gray Iron

Introduction

GRAY IRON refers to a broad class of ferrous casting alloys normally characterized by a microstructure of flake graphite in a ferrous matrix. Gray irons are in essence iron-carbon-silicon alloys that usually contain 2.5 to 4% C, 1 to 3% Si, and additions of manganese, depending on the desired microstructure (as low as 0.1% Mn in ferritic gray irons and as high as 1.2% Mn in pearlitics). Sulfur and phosphorus are also present in small amounts as residual impurities. More highly alloyed (>4% alloy content) austenitic nickel-alloyed gray irons can also be produced, as well as high-silicon-content gray irons used for corrosion-resistant and/or heat-resistant applications. These materials are described in the article "Alloy Cast Irons" in this Section.

Classes of Gray Iron

A simple and convenient classification of the gray irons is found in ASTM specification A 48, which classifies the various types in terms of tensile strength expressed in ksi. The ASTM classification by no means connotes a scale of ascending superiority from class 20 (minimum tensile strength of 140 MPa or 20 ksi) to class 60 (minimum tensile strength of 410 MPa, or 60 ksi). In many applications, strength is not the major criterion for the choice of grade. For example, for parts such as clutch plates and brake drums, where resistance to heat checking is important, low-strength grades of iron are the superior performers. Similarly, in heat-shock applications such as ingot or pig molds, a class 60 iron would fail quickly whereas good performance is shown by class 25 iron. In machine tools and other parts subject to vibrations, the better damping capacity of low-strength irons is often advantageous.

Generally, it can be assumed that the following properties of gray cast irons increase with increasing tensile strength from classes 20 to 60:

- All strengths, including strength at elevated temperature
- Ability to be machined to a fine finish
- Modulus of elasticity
- Wear resistance

On the other hand, the following properties decrease with increasing tensile strength, so that low-strength irons often perform better that high-strength irons when these properties are important:

- Machinability
- Resistance to thermal shock
- Damping capacity
- Ability to be cast in thin sections

Composition. The major elements in gray iron are carbon, silicon, and iron. Carbon and silicon levels found in commercial irons vary widely:

Type of iron	**Total carbon, %**	Silicon, %
Class 20	3.40-3.60	**2.30-2.50**
Class 30	3.10-3.30	**2.10-2.30**
Class 40	2.95-3.15	**1.70-2.00**
Class 50	2.70-3.00	**1.70-2.00**
Class 60	**2.50-2.85**	**1.90-2.10**

Castability

Successful production of a gray iron casting depends on the fluidity of the molten metal and on the cooling rate, which is influenced by the minimum section thickness and by section thickness variations. As described below, casting design is often described in terms of section sensitivity. This is an attempt to correlate properties in critical sections of the casting with the combined effects of composition and cooling rate. All of these factors are related and may be condensed into a single term, *castability,* which for gray iron can be defined as the minimum section thickness that can be produced in a mold cavity with a given volume/area ratio and mechanical properties consistent with the type of iron being poured.

Fluidity. Scrap losses resulting from misruns, cold shuts, and round corners are often attributed to the lack of fluidity of the metal being poured.

Mold conditions, pouring rate, and other process variables being equal, the fluidity of commercial gray irons depends primarily on the amount of superheat above the freezing temperature (liquidus). As the total carbon (TC) content decreases, the liquidus temperature increases, and the fluidity at a given pouring temperature therefore decreases. Fluidity is commonly measured as the length of flow into a spiral-type fluidity test mold. The relation between fluidity and superheat is shown in Fig. 1 and Table 1 for unalloyed gray irons of different carbon contents.

Table 1 Superheat above liquidus for 2% Si irons of various carbon contents poured at 1455 °C (2650 °F)

Carbon, %	**Liquidus temperature**		Superheat above liquidus	
	°C	**°F**	**°C**	°F
2.52	1295	2360	160	**290**
3.04	1245	2270	210	**380**

3.60	**1175**	**2150**	**280**	**500**

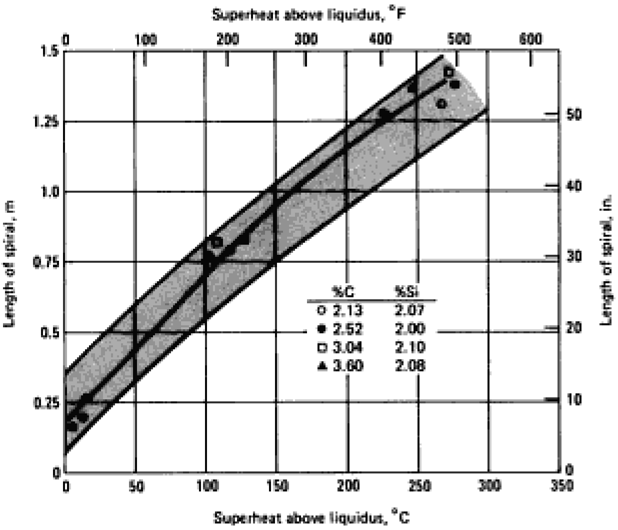


Fig. 1 Fluidity versus degree of superheat for four gray irons of different carbon contents

Microstructure

The usual microstructure of gray iron is a matrix predominantly of pearlite, with graphite flakes dispersed throughout (Fig. 2). Foundry practice can be varied so that nucleation and growth of graphite flakes occur in a pattern that enhances the desired properties. The amount, size, and distribution of graphite are important. Cooling that is too rapid may produce "mottled iron," in which carbon is present in the form of both primary cementite (iron carbide) and graphite. Very slow cooling of irons that contain large percentages of silicon and carbon is likely to produce a matrix predominantly of ferrite, together with coarse graphite flakes.

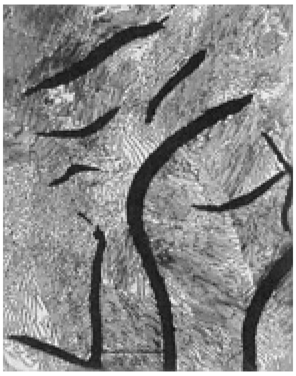


Fig. 2 Class 30 gray iron, as-cast. Structure consists of type A graphite in a pearlitic matrix.

Graphite Morphology. The mechanical and physical properties of gray iron are governed in part by the shape, size, amount, and distribution of the graphite flakes. A method for evaluating graphite-flake distribution and size is given in ASTM A 247. There are five graphite-flake distributions: A to E (Fig. 3).

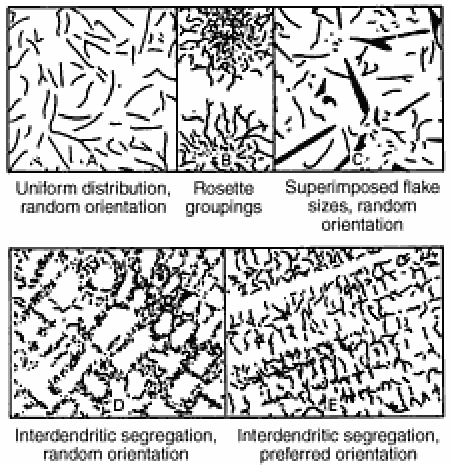

A
Uniform distribution, random orientation
B
Rosette groupings
C
Superimposed flake sizes, random orientation
D
Interdendritic segregation, random orientation
E
Interdendritic segregation, preferred orientation

Fig. 3 Graphite distributions specified in ASTM A 247

Type A graphite flakes are randomly distributed and oriented throughout the iron matrix (Fig. 2). This type of graphite is found in irons that solidify with a minimum amount of undercooling, and type A is the structure desired if mechanical properties are to be optimized.

Type B graphite (rosette pattern) is formed in irons of near-eutectic composition that solidify with a greater amount of undercooling than that associated with type A graphite. Type B flake graphite is common with moderately thin sections (about 10 mm, or $\frac{3}{8}$ in.) and along the surface of thicker sections.

Types D and E graphite form when the amount of undercooling is high but is not sufficient to cause carbide formation. Both types are found in interdendritic regions. Type D graphite is randomly distributed while type E flakes have a preferred orientation. The manner in which the plane of polish intersects the graphite flakes may be responsible for this difference in orientation. Elements such as titanium and aluminum promote undercooled graphite structures. The iron matrix associated with undercooled graphite is usually ferrite, because formation of the fine, highly branched flakes reduces carbon diffusion distances and results in a low-carbon matrix. Because ferrite has a lower tensile strength than pearlite, there is a reduction in the anticipated strength of the iron.

Type C graphite occurs in hypereutectic irons, particularly those with a high carbon content. Type C graphite precipitates during the primary freezing of the iron. Kish graphite, as it is often called, appears as straight, coarse plates. It greatly reduces the mechanical properties of the iron and produces a rough surface finish when machined. However, type C graphite is desirable in applications requiring a high degree of heat transfer.

Graphite-flake sizes also influence properties. Large flakes are associated with irons having high *CE* values and slow cooling rates. Strongly hypoeutectic irons and irons subjected to rapid solidification generally exhibit small, short flakes. The large flakes are desirable in applications requiring high-thermal conductivity and damping capacity. Small flakes, because they disrupt the matrix to a lesser extent, are desired when maximum tensile properties and a fine, smooth surface finish are needed.

Section Sensitivity

In practice, the minimum thickness of section in which any given class of gray iron may be poured is more likely to depend on the cooling rate of the section than on the fluidity of the metal. For example, although a plate 300 mm (12 in.) square by 6 mm (0.25 in.) thick can be poured classes 50 and 25 iron, the class 50 casting would not be gray iron, because the cooling rate would be so rapid that massive carbides would be formed. Yet it is entirely feasible to use class 50 iron for a diesel-engine cylinder head that has predominantly 6 mm (0.25 in.) wall sections in the water jackets above the firing deck. This is simply because the cooling rate of the cylinder head has been reduced by the "mass effect" resulting from enclosed cores and the proximity (often less than 12 mm, or 0.50 in.) of one 6 mm (0.25 in.) wall to the other.

It should be recognized that the smallest section that can be cast gray, without massive carbides, depends not only on metal composition but also on foundry practices. For example, by adjusting silicon content or by adding inoculants (graphitizing agents) to the ladle (or, more effectively, to the stream as the mold is poured), the foundryman may decrease the minimum section size for freedom from carbides for a given basic composition of gray iron.

Typical Effects of Section Size. When a wedge-shape bar with about 10° taper cast in a sand mold and sectioned near the center of its length, and Rockwell hardness determinations are made on the cut surface from the point of the wedge progressively into the thicker sections, the curves so determined to show what extent continually increasing section size will affect hardness, as shown in Fig. 4

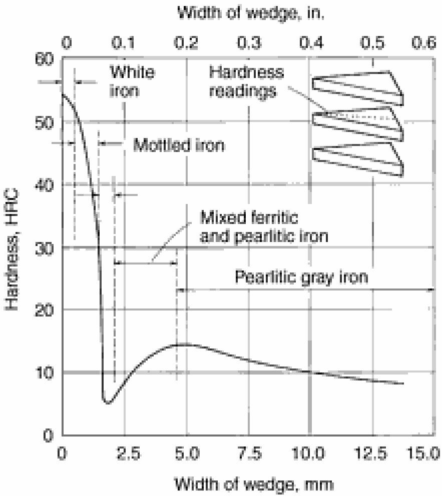


Fig. 4 Effect of section thickness and structure. Hardness readings were taken at increasing distance from the tip of a cast wedge section, as shown by inset. Composition of iron: 3.52% C, 2.55% Si, 1.01% Mn, 0.215% P, and 0.086% S

Progressing along the curve from the left in Fig. 4, the following metallographic constituents occur. The tip of the wedge is white iron (a mixture of carbide and pearlite) with hardness greater than 50 HRC. As the iron becomes mottled (a mixture of white iron and gray iron), the hardness decreases sharply. A minimum is reached because of the occurrence of fine type D flake graphite, which usually has large amounts of ferrite. With a slightly lower cooling rate, the structure becomes fine type A flake graphite in a pearlite matrix, and the hardness rises to another maximum on the curve. This structure usually is the most desirable for resistance and strength. With increasing section thickness beyond this point, the graphite flakes become coarser and the pearlite lamellae more widely spaced, resulting in slightly lower hardness. With further increase in wedge thickness and decrease in cooling rate, pearlite decomposes progressively into a mixture of ferrite and graphite, resulting in softer and weaker iron.

The structures of most commercial gray iron castings are represented by the right-hand downward-sloping portion of the curve in Fig. 4, beyond 5 mm (0.20 in.) wedge thickness, and normally increasing section size is reflected by gradual lowering of hardness and strength. However, thin sections may be represented by the left-hand downward-sloping portion.

Figure 5 shows the effect of varying section size of tensile strength for various classes of iron. Tensile strength decreases with increasing section size for all classes of gray iron. For example, an iron with a tensile strength of 310 MPa (45 ksi) in a 25 mm (1 in.) section will develop only 207 MPa (30 ksi) in a 75 mm (3 in.) section because of the decreased cooling rate associated with the larger section. This reduction in tensile strength is caused by the presence of larger graphite flakes and by a reduction in combined carbon. Decreasing combined carbon results in an increase in the amount of ferrite found, either a coarser pearlite spacing or the appearance of a ferrite phase.

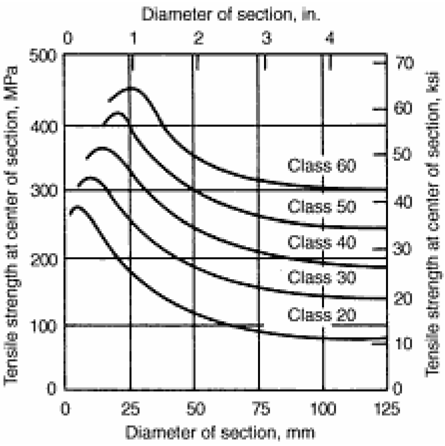


Fig. 5 Effect of section size on tensile strength of specimens cast from five classes of gray iron

The maximum strength of class 20 iron occurs at a smaller section size than for class 60 iron. Each class has a minimum section size that can be cast without the formation of iron carbide. Recommended minimum section sizes are listed in Table 2 for each class of unalloyed gray iron. It is important for both the foundryworker and the designer to recognize that each class of iron has a minimum section size in which it can be cast without the presence of chill and that this minimum increases with higher classes of gray iron.

Table 2 Minimum recommended section sizes for unalloyed gray irons

Class	**Minimum section thickness**		Volume-to-surface-area ratio[(a)]	
	mm	**in.**	**mm**	in.
20	3.2	$\frac{1}{8}$	1.5	**0.06**
25	6.4	$\frac{1}{4}$	3.0	**0.12**
30	9.5	$\frac{3}{8}$	4.3	**0.17**
35	9.5	$\frac{3}{8}$	4.3	**0.17**
40	15.9	$\frac{5}{8}$	7.1	**0.28**
50	19.0	$\frac{3}{4}$	8.4	**0.33**

(a) Volume-to-surface-area ratios are for square plates.

Prevailing Sections

Although the ASTM size B test bar (30.5 mm, or 1.2 in., diameter) is the bar most commonly used for all gray irons from classes 20 to 60, ASTM A 48 provides a series of bar sizes, and the user can select the bar sizes that best approximates the cooling rate in the critical section of the casting. In practice, it is customary to be somewhat more definite about the recommended values of minimum prevailing casting section for the various ASTM classes of cast iron (Table 2). The prevailing sections should be free of carbidic areas. In a platelike section, occasional thinner walls (such as ribs) are of no importance unless they are very thin or are appended to the outer edges of the casting.

Figure 6 shows mechanical properties of classes 30 and 50 gray irons in various sections. For class 30 iron, the combined carbon content and hardness are still at a safe level in sections equivalent to a 10 mm (0.4 in.) plate, which has a volume-to-area (*V*/*T*) ratio of about 5 mm (0.20 in.). For class 50 iron, however, both combined carbon and Brinell hardness (HB) show marked increases when the thickness of the equivalent plate section is decreased to about 15 mm (0.6 in.), with *V*/*A* ratio ~7 mm (0.27 in.). These results are consistent with the recommendations in Table 2.

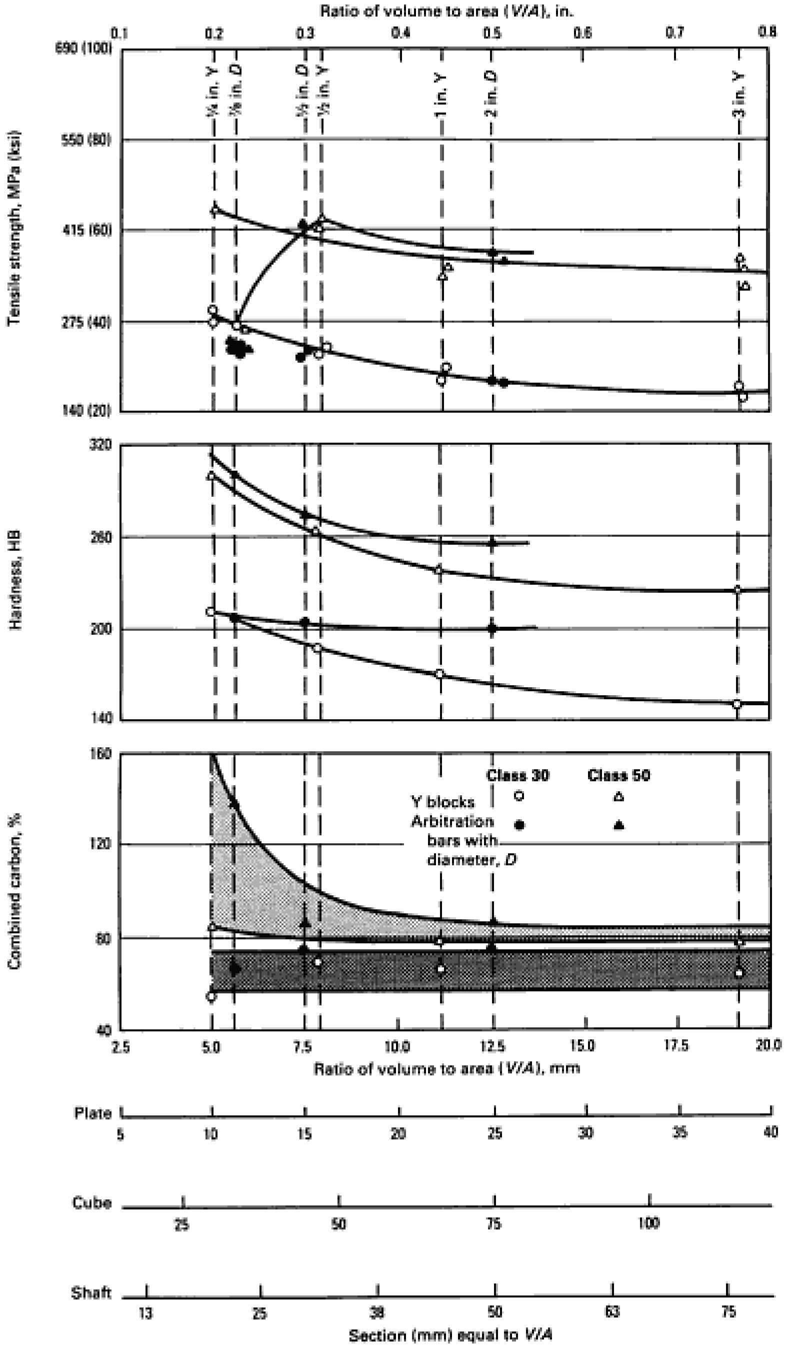


Fig. 6 Mechanical properties of class 30 and class 50 gray iron as a function of section size. Composition of the class 30 iron: 3.40% C, 2.38% Si, 0.71% Mn, 0.423% P, and 0.152% S. Composition of the class 50 iron: 2.96% C, 1.63% Si, 1.05% Mn, 0.67% Mo, 0.114% P, and 0.072% S

The hazards involved in pouring a given class of gray iron in a plate section thinner than recommended are discovered when the casting is machined. Typical losses are a result of specifying too high a strength for a prevailing section of 9.5 mm ($\frac{3}{8}$ in.) are:

Class	Rejections, %

35	**Negligible**
45	**25**
55	**80-100**

Rejections were for "hard spots" that made it impossible to machine the castings by normal methods.

In marginal applications, a higher class of iron can sometimes be used if the casting is cooled slowly (in effect, increasing the section thickness) by judicious placement of flowoffs and risers.

Test Bar Properties

Mechanical property values obtained from test bars are sometimes the only available guides to the actual mechanical properties of the metal in production castings. When test bars and castings are both poured from the same metal and have subsequent thermal histories that are nearly identical, the strength of the test bars gives a general indication of strength of the metal in the castings. However, test bar results cannot be assumed to represent accurately the properties of the metal in every section of every casting, because of differences in section size and cooling rate.

Usual Tests. Tension and transverse tests on bars cast specifically for such tests are the most common for evaluating the strength of gray iron.

Yield strength, elongation, and reduction of area are seldom determined for gray iron in standard tension tests. The transverse test measures strength in bending and has the additional advantage that a defection value may be obtained readily. Table 3 gives minimum specification values. Data usually can be obtained faster from the transverse test than from the tension test because machining of the specimen is unnecessary in transverse testing. The surface condition of the bar will affect the transverse test but not the tension test made on a machined specimen. Conversely, the presence of coarse graphite in the center of the bar, which can occur in an iron that is very section sensitive, will affect the tension test but not the transverse test.

Table 3 Transverse breaking loads of gray irons tested per ASTM A 438

ASTM class[(a)]	**Approximate tensile strength**		Corrected transverse breaking load[(a)]					
			A bar[(b)]		**B bar**[(c)]		C bar[(d)]	
	MPa	**ksi**	**kN**	**lbf**	**kN**	**lbf**	**kN**	lbf
20	138	20	4.00	900	8.01	1800	26.69	**6,000**
25	172	25	4.56	1025	8.90	2000	30.25	**6,800**
30	207	30	5.12	1150	9.79	2200	33.81	**7,600**
35	241	35	5.67	1275	10.68	2400	36.92	**8,300**
40	276	40	6.23	1400	11.57	2600	40.48	**9,100**

45	310	45	6.85	1540	12.46	2800	43.15	**9,700**
50	345	50	7.45	1675	13.34	3000	48.04	**10,300**
60	**414**	**60**	**8.56**	**1925**	**15.12**	**3400**	**55.60**	**12,500**

(a) For separately cast test specimens produced in accordance with ASTM A 48, ASTM A 278, ASME SA278, FED QQ-1-652, or any other specification that designates ASTM A 438 as the test method. Included in specifications only by agreement between producer and purchaser.

(b) 22.4 mm (0.88 in.) diam; 305 mm (12 in.) between supports.

(c) 30.5 mm (1.20 in.) diam; 457 mm (18 in.) between supports.

(d) 50.8 mm (2.00 in.) diam; 610 mm (24 in.) between supports

Typical Specifications. ASTM A 48 is typical of specifications based on test bars. In practice, separately cast test bars in one of three different standard sizes are used to evaluate the properties in the controlling section of the castings. After manufacturer and purchaser agree on a controlling section of the casting, the size of test bar that corresponds, approximately to the cooling rate expected in that section is specified by letter (see Table 4).

Table 4 Test bars designed to match controlling sections of castings (ASTM A 48)

Controlling section		**Test bar**	Diameter of as-cast test bar	
in.	**mm**		**mm**	in.
<0.25	<6	S	(a)	**(a)**
0.25-0.50	6-12	A	22.4	**0.88**
0.51-1.00	13-25	B	30.5	**1.20**
1.01-2.00	26-50	C	50.8	**2.00**

(a) All dimensions of test bar by agreement between manufacturer and purchaser

Most gray iron castings for general engineering use are specified as class 25, 30, or 35. Specification A 48 is based entirely on mechanical properties, and the composition that provides the required properties can be selected by the individual producer. A manufacturer whose major production is medium-section castings of class 35 iron will find, for heavy-section castings where the 50 mm (2 in.) test bar is required for qualifying, that the same composition will not meet the requirements for class 35. It will qualify only for a lower class, such as 25 or 30. As thickness of the controlling section increases, the composition must be adjusted to maintain the same tensile strength.

ASTM specifications other than A 48 include A 159 (automotive), A 126 (valves, flanges, and pipe fitttings), A 74 (soil pipe and fittings), A 278 (pressure-containing parts for temperatures up to 340 °C, or 650 °F), A 319 (nonpressure-containing parts for elevated-temperature service), A 823 (permanent-mold cast gray irons), and A 436 (austenitic gray irons for heat, corrosion, and wear resistance). Gray irons used for automotive applications are also described in SAE standard J 431.

Compressive Strength. When gray iron is used for structural applications such as machinery foundations or supports, the engineer is usually designing to support weight only, and bases calculations on the compressive strength of materials. Table 5, which summarizes typical values for mechanical properties of the various grades, shows the high compressive strength of gray irons. If loads other than dead weights are involved (unless these loads are constant), the problem is dynamic stresses, which are discussed later in this article.

Table 5 Typical mechanical properties of as-cast standard gray iron test bars

ASTM A48 class	**Tensile strength**		**Torsional shear strength**		**Compressive strength**		**Reversed bending fatigue limit**		**Transverse load on test bar B**		Hardness, HB
	MPa	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**kN**	**lbf**	
20	152	22	179	26	572	83	69	10	8.23	1850	**156**
25	179	26	220	32	669	97	79	11.5	9.67	2175	**174**
30	214	31	276	40	752	109	97	14	11.23	2525	**210**
35	252	36.5	334	48.5	855	124	110	16	12.68	2850	**212**
40	293	42.5	393	57	965	140	128	18.5	14.12	3175	**235**
50	362	52.5	503	73	1130	164	148	21.5	16.01	3600	**262**
60	**431**	**62.5**	**610**	**88.5**	**1293**	**187.5**	**169**	**24.5**	**16.46**	**3700**	**302**

Tensile strength is considered in selecting gray iron for parts intended for static load in direct tension or bending. Such parts include pressure vessels, autoclaves, housings, and other enclosures, valves, fittings, and levers. Depending on the uncertainty of loading, safety factors of 2 to 12 have been used in figuring allowable design stresses. Typical tensile strength valves are given in Tables 3 and 5.

Transverse Strength and Deflection. When an arbitration bar is loaded as a simple beam and the load and deflection required to break it are determined, the resulting value is converted into a nominal index of strength by using the standard beam formula. The value so determined is arbitrarily called the "modulus of rupture." The values for modulus of rupture are useful for production control, but cannot be used in the design of castings without further analysis and interpretation. Typical transverse breaking loads for gray irons are given in Tables 3 and 5.

Elongation of gray iron at fracture is very small (on the order of 0.6%) and hence is seldom reported. The designer cannot use the numerical value of permanent elongation in any quantitative manner.

Torsional Shear Strength. As shown in Table 5, most gray irons have high-torsional shear strength. Many grades have torsional strength greater than some grades of steel. This characteristic, along with low-notch sensitivity, make gray iron a suitable material for shafting of various types, particularly in the grades of higher tensile strength.

Modulus of Elasticity. Typical stress-strain curves for gray iron are shown in Fig. 7. Gray iron does not obey Hooke's law, and the modulus in tension is usually determined arbitrarily as the slope of the line connecting the origin of the stress-strain curve with the point corresponding to $\frac{1}{4}$ of the tensile strength (secant modulus). Some engineers use the slope of the stress-strain curve near the origin (tangent modulus).

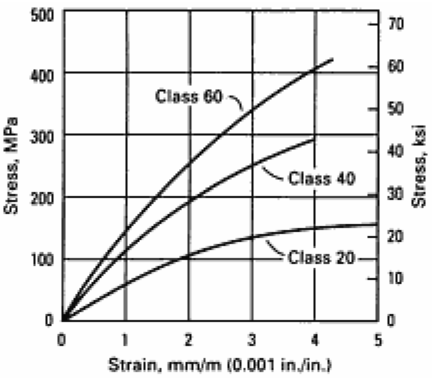


Fig. 7 Typical stress-strain curves for three classes of gray iron in tension

Hardness of gray iron, as measured by Brinell or Rockwell testers, is an intermediate value between the hardness of the soft graphite in the iron and that of the harder metallic matrix. Variations in graphite size and distribution will cause wide variations in hardness (particularly Rockwell hardness) even though the hardness of the metallic matrix is constant. To illustrate this effect, matrix microhardness measurements for five types of hardened iron, as compared with Rockwell C measurements on the same iron, are shown in Table 6.

Table 6 Influence of graphite type and distribution on the hardness of hardened gray irons

Type of graphite	**Total carbon, %**	**Conventional hardness, HRC[(a)]**	Matrix hardness, HRC[(b)]
A	3.06	45.2[(c)]	**61.5**
A	3.53	43.1	**61.0**
A	4.00	32.0	**62.0**
D	3.30	54.0	**62.5**
D	**3.60**	**48.7**	**60.5**

(a) Measured by conventional Rockwell C test.

(b) Hardness of matrix, measured with superficial hardness tester and converted to Rockwell C.

(c) Although this value was obtained in the specific test cited, it is not typical of gray iron of 3.06% C. Ordinarily the hardness of such iron is 48 to 50 HRC.

If any hardness correlation is to be attempted, the type and amount of graphite must be constant in the irons being compared. Rockwell hardness tests are considered appropriate only for hardened castings (camshafts, for example), and even hardened castings, Brinell tests are preferred. Brinell tests must be used when attempting any strength correlations for unhardened castings.

Fatigue Limit in Reversed Bending

Because fatigue limits are expensive to determine, the designer usually has incomplete information on this property. Figure 8 shows fatigue-life curves at room temperature for a gray iron under completely reversed cycles of bending stress. Each point represents the data from one specimen. Table 5 list additional data.

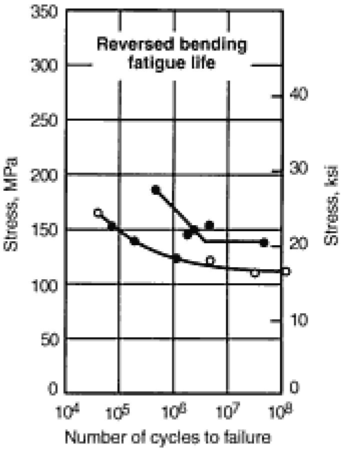


Fig. 8 Reversed bending fatigue life at room temperature for gray iron containing 2.84% C, 1.52% Si, 1.05% Mn, 0.07% P, 0.12% S, 0.31% Cr, 0.20% Ni, and 0.37% Cu. Open circles represent notched specimens; closed circles represent unnotched specimens.

Axial loading or torsional loading cycles are frequently encountered in designing parts of cast iron, and in many instances these are not completely reversed loads. Types of regularly repeated stress variation can usually be expressed as a function of a mean stress and a stress range. Whenever possible, the designer should use actual data from the limited information available.

If precisely applicable test data are not available, the reversed bending fatigue limit of machined parts may be estimated as about 35% of the minimum specified tensile strength of the particular grade of gray iron being considered. This value is probably more conservative than an average of the limited data available on the fatigue limit for gray iron.

Ductile Iron

Introduction

DUCTILE CAST IRON, also known as nodular iron or spheroidal-graphite (SG) cast iron, is cast iron in which the graphite is present as tiny spheres (nodules) (see Fig. 1). In ductile iron, eutectic graphite separates from the molten iron during solidification in an manner similar to that in which eutectic graphite separates in gray cast iron. However, because of additives introduced in the molten iron before casting, the graphite grows as spheres, rather than as flakes of any of the forms characteristic of gray iron. Cast iron containing spheroidal graphite is much stronger and has higher elongation than gray iron or malleable iron. It may be considered a natural composite in which the spheroidal graphite imparts unique properties to ductile iron.

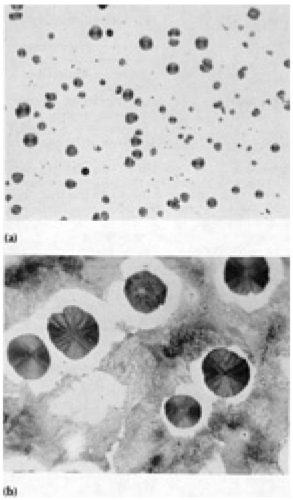


Fig. 1 Spheroidal graphite in an unetched ductile iron matrix shown at 75× (a) and in the etched (picral) condition shown at 300× (b). Etching reveals that the matrix consists of ferritic envelopes around the graphite nodules (bull's-eye structure) surrounded by a pearlitic matrix.

The relatively high strength and toughness of ductile iron give it an advantage over gray iron or malleable iron in many structural applications. Also, because ductile iron does not require heat treatment to product graphite nodules (as malleable iron does to produce temper-carbon nodules), it can compete with malleable iron even though it requires a melt treatment and inoculation process. The mold yield is normally higher than with malleable iron. Ductile iron can be produced to x-ray standards because porosity stays in the thermal center. Malleable iron cannot tolerate porosity because voids migrate to the surface of hot spots such as fillets and appear as cracks.

General Characteristics of Ductile Irons

Typically, the composition of unalloyed ductile iron differs from that of gray iron or malleable iron (Table 1). The raw materials used for ductile iron must be of higher purity. Like gray iron, ductile iron can be melted in cupolas, electric arc furnaces, or induction furnaces. Ductile iron, as a liquid, has high fluidity, excellent castability, but high surface tension. The sands and molding equipment used for ductile iron must provide rigid molds of high density and good heat transfer.

Table 1 Typical composition ranges for unalloyed cast irons

Type	Composition, %										
	TC[(a)]	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**Cu**	**P**	**S**	**Ce**	Mg
Gray iron	3.25-3.50	0.50-0.90	1.80-2.30	0.05-0.45	0.05-0.20	0.05-0.10	0.15-0.40	0.12 max	0.15 max	. . .	. . .
Malleable iron	2.45-2.55	0.35-0.55	1.40-1.50	0.04-0.07	0.05-0.30	0.03-0.10	0.03-0.40	0.03 max	0.05-0.07	. . .	. . .
Ductile iron	**3.60-3.80**	**0.15-1.00**	**1.80-2.80**	**0.03-0.07**	**0.05-0.20**	**0.01-0.10**	**0.15-1.00**	**0.03 max**	**0.002 max**	**0.005-0.20**[(b)]	**0.03-0.06**

(a) TC, total carbon.

(b) Optional

Solidification and Shrinkage Characteristics. The formation of graphite during solidification causes an attendant increase in volume, which can counteract the loss in volume due to the liquid-to-solid phase change in the metallic constituent. Ductile iron castings typically require only minimal use of risers (reservoirs in the mold that feed molten metal into the mold cavity to compensate for liquid contraction during cooling and solidification). Gray irons often do not require risers to ensure shrinkage-free castings. On the other hand, steels and malleable iron generally require heavy risering. Thus, the mold yield of ductile iron castings (the ratio of the weight of usable castings to the weight of metal poured) is much higher than the mold yield of either steel castings or malleable iron castings, but not as high as that of gray iron. In some cases, ductile iron castings have been made without risers.

Often designers must compensate for the shrinkage of cast iron (during both solidification and subsequent cooling to room temperature) by making patterns with dimensions larger than those desired in the finished castings. Typically, ductile iron requires less compensation than any other cast ferrous metal. The allowances in patternmaker rules (shrink rules) are usually:

Type of cast metal	Shrinkage allowance, %
Ductile iron	**0-0.7**
Gray iron	**1.0**
Malleable iron	**1.0**
Austenitic alloy iron	**1.3-1.5**

White iron	**2.0**
Carbon steel	**2.0**
Alloy steel	**2.5**

Shrinkage allowance can vary somewhat from the percentages given above, and different percentages must often be used for different directions in one casting because of the influence of the solidification pattern on the amount of contraction that takes place in different directions. Shrinkage is volumetric, and the ratio of dimensions to volume influences each dimension. As ductile iron approaches a condition of shrinkage porosity, the graphite nodules tend to become aligned and can result in lower fatigue strength.

As-Cast versus Heat Treated. Most ductile iron castings are used as-cast, but in some foundries, some castings are heat treated before being shipped. Heat treatment varies according to the desired effect on properties. Any heat treatment, with the exception of austempering, reduces fatigue properties. Holding at subcritical (705 °C, or 1300 °F) temperature for no more than 4 h improves fracture resistance. Heating castings above 790 °C (1450 °F) followed by fast cooling (oil quench or air quench) significantly reduces fatigue strength and fracture resistance at temperatures above room temperature. Ferritizing by heating to 900 °C (1650 °F) and slow cooling has the same effects. Heating to above the critical temperature also reduces the combined carbon content of quenched and tempered microstructures and produces lower tensile strength and wear resistance than the same hardness produced as-cast. Some castings may be given hardening treatments (either localized surface or through hardened) that produce bainitic or martensitic matrices.

As the matrix structure is varied progressively from ferrite to ferrite and pearlite to pearlite to bainite and finally to martensite, hardness, strength, and wear resistance increase, but impact resistance, ductility, and machinability decrease. An exception to this is austempered ductile iron, in which considerable elongation (as high as 10%) can be obtained even at high strengths (1000 MPa, or 145 ksi). Austempered ductile iron (ADI) has a matrix that is a combination of acicular (bainitic) ferrite and stabilized austenite (Fig. 2).

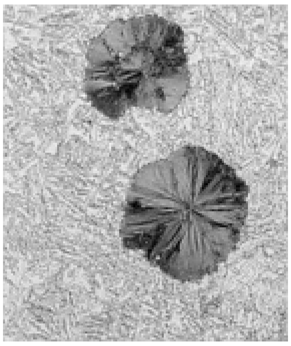


Fig. 2 Austempered ductile iron structure consisting of spheroidal graphite in a matrix of bainitic ferritic plates (dark) and interplate austenite (white)

Alloying. Ductile iron can be alloyed with small amounts of nickel, molybdenum, or copper to improve its strength and hardenability. The addition of molybdenum is done with caution because of the tendency for intercellular segregation. Larger amounts of silicon, chromium, nickel, or copper can be added for improved resistance to corrosion, oxidation or abrasion, or for high-temperature applications.

Specifications

Most of the specifications for standard grades of ductile iron are based on properties. That is, strength and/or hardness is specified for each grade of ductile iron, and composition is either loosely specified or made subordinate to mechanical properties. Tables 2 and 3 list compositions, properties, and typical applications for most of the standard ductile irons that are defined by current standard specifications (expect for the high-nickel, corrosion-resistant, and heat-resistant irons defined in ASTM A 439). As shown in Table 3, the ASTM system for designating the grade of ductile iron incorporates the numbers indicating tensile strength in ksi, yield strength in ksi, and elongation in percent. This system makes it easy to specify nonstandard grades that meet the general requirements of ASTM A 536. For example, grade 80-60-03 (552 MPa, or 80 ksi, minimum tensile strength; 414 MPa, or 60 ksi, yield strength; and 3% elongation) is widely used in applications for which relatively high ductility is not important. Grades 65-45-12 and 60-40-18 are used in areas requiring high ductility and impact resistance. Grades 60-42-10 and 70-50-05 are used for special applications such as annealed pipe or cast fittings. Grades other than those listed in ASTM A 536 or mentioned above can be made to the general requirements of A 536, but with the mechanical properties specified by mutual agreement between purchaser and producer.

Table 2 Compositions and general uses for standard grades of ductile iron

Specification No.	**Grade or class**	**UNS**	**TC(a)**	**Typical composition, %**				**Description**	General uses
				Si	**Mn**	**P**	**S**		
ASTM A 395; ASME SA395	60-40-18	F32800	3.00 min	2.50 max(b)	. . .	0.08 max	. . .	Ferritic; annealed	**Pressure-containing parts for use at elevated temperatures**
ASTM A 476; SAE AMS 5316C	80-60-03	F34100	3.00 min(c)	3.0 max	. . .	0.08 max	0.05 max	As-cast	**Paper mill dryer rolls, at temperatures up to 230 °C (450 °F)**
ASTM A 536	60-40-18(d)	F32800	. . .	. . .	. . .	. . .	. . .	Ferritic; may be annealed	**Shock-resistant parts; low-temperature service**
	65-45-12(d)	F33100	. . .	. . .	. . .	. . .	. . .	Mostly ferritic; as-cast or annealed	**General service**
	80-55-06(d)	F33800	. . .	. . .	. . .	. . .	. . .	Ferritic/pearlitic; as-cast	**General service**
	100-70-03(d)	F34800	. . .	. . .	. . .	. . .	. . .	Mostly pearlitic; may be normalized	**Best combination of strength and wear resistance and best response to surface hardening**
	120-90-02(d)	F36200	. . .	. . .	. . .	. . .	. . .	Martensitic; oil quenched and tempered	**Highest strength and wear resistance**
ASTM A 716	60-42-10	F32900	. . .	. . .	. . .	. . .	. . .	Centrifugally cast	**Culvert pipe**
ASTM A 746	60-42-10	. . .	. . .	. . .	. . .	. . .	. . .	Centrifugally cast	**Gravity sewer pipe**
ASTM A 874(e)	45-30-	. . .	3.0-	1.2-	0.25	0.03	. . .	Ferritic	**Low-temperature service**

	12		37	2.3	max	max			
SAE J434	D4018(f)	F32800	3.20-4.10	1.80-3.00	0.10-1.00	0.015-0.10	0.005-0.035	Ferritic	**Moderately stressed parts requiring good ductility and machinability**
	D4512(f)	F33100	. . .	. . .	. . .	. . .	. . .	Ferritic/pearlitic	**Moderately stressed parts requiring moderate machinability**
	D5506(f)	F33800	. . .	. . .	. . .	. . .	. . .	Ferritic/pearlitic	**Highly stressed parts requiring good toughness**
	D7003(f)	F34800	. . .	. . .	. . .	. . .	. . .	Pearlitic	**Highly stressed parts requiring very good wear resistance and good response to selective hardening**
	DQ&T(f)	F30000	. . .	. . .	. . .	. . .	. . .	Martensitic	**Highly stressed parts requiring uniformity of microstructure and close control of properties**
SAE AMS 5315C	**Class A**	**F33101**	**3.0 min**	**2.50 max(g)**	**. . .**	**0.08 max**	**. . .**	**Ferritic; annealed**	**General shipboard service**

Note: For mechanical properties and typical applications, see Table 3.

(a) TC, total carbon.

(b) The silicon limit may be increased by 0.08%, up to 2.75 Si, for each 0.01% reduction in phosphorus content.

(c) Carbon equivalent, *CE*, 3.8-4.5; *CE* = TC + 0.3 (Si + P).

(d) Composition subordinate to mechanical properties; composition range for any element may be specified by agreement between supplier and purchaser.

(e) Also contains 0.07% Mg (max), 0.1% Cu (max), 1.0% Ni (max), and 0.07% Cr (max).

(f) General composition given under grade D4018 for reference only. Typically, foundries will produce to narrower ranges than those shown and will establish different median compositions for different grades.

(g) For castings with sections 13 mm ($\frac{1}{2}$ in.) and smaller, may have 2.75 Si max with 0.08 P max, or 3.00 Si max with 0.05 P max; for castings with section 50 mm (2 in.) and greater, *CE* must not exceed 4.3.

Table 3 Mechanical properties and typical applications for standard grades of ductile iron

Specification No.	**Grade or class**	**Hardness, HB**[(a)]	**Tensile strength, min**[(b)]		**Yield strength, min**[(b)]		**Elongation in 50 mm (2 in.) (min), %**[(b)]	Typical applications
			MPa	**ksi**	**MPa**	**ksi**		
ASTM A 395; ASME SA395	60-40-18	143-187	414	60	276	40	18	**Valves and fittings for steam and chemical plant equipment**
ASTM A 476[(c)]; SAE AMS 5316	80-60-03	201 min	552	80	414	60	3	**Paper mill dryer rolls**
ASTM A 536	60-40-18	. . .	414	60	276	40	18	**Pressure-containing parts such as valve and pump bodies**
	65-45-12	. . .	448	65	310	45	12	**Machine components subject to shock and fatigue loads**
	80-55-06	. . .	552	80	379	55	6	**Crankshafts, gears, and rollers**
	100-70-03	. . .	689	100	483	70	3	**High-strength gears and machine components**
	120-90-02	. . .	827	120	621	90	2	**Pinions, gears, rollers, and slides**
SAE J434	D4018	170 max	414	60	276	40	18	**Steering knuckles**
	D4512	156-217	448	65	310	45	12	**Disk brake calipers**
	D5506	187-255	552	80	379	55	6	**Crankshafts**
	D7003	241-302	689	100	483	70	3	**Gears**
	DQ&T	[(c)]	[(d)]	[(d)]	[(d)]	[(d)]	[(d)]	**Rocker arms**
SAE AMS 5315C	**Class A**	**190 max**	**414**	**60**	**310**	**45**	**15**	**Electric equipment, engine blocks, pumps, housings, gears, valve bodies, clamps, and cylinders**

Note: For compositions, descriptions, and uses, see Table 2.

(a) Measured at a predetermined location on the casting.

(b) Determined using a standard specimen taken from a separately cast test block, as set forth in the applicable specification.

(c) Range specified by mutual agreement between producer and purchaser.

(d) Value must be compatible with minimum hardness specified for production castings.

The Society of Automotive Engineers (now SAE International) uses a method of specifying iron for castings produced in larger quantities that is based on the microstructure and Brinell hardness of the material in the castings themselves. Both ASTM and SAE specifications are standards for tensile properties and hardness. The tensile properties are quasistatic and may not indicate the dynamic properties such as impact or fatigue strength.

Specifications for the highest-strength grades usually mention the possibility of hardened and tempered structures, but ASTM A 897 (Table 4) should be consulted for the most recently reported austempered ductile irons, which have the highest combinations of tensile strength and ductility.

Table 4 ASTM standard A 897-90 and A 897M-90 mechanical property requirements of austempered ductile iron

Grade	**Tensile (min)**		**Yield (min)**		**Elongation, %**	**Impact(a)**		Hardness, HB(c)
	MPa	**ksi**	**MPa**	**ksi**		**J**	**ft · lbf**	
125-80-10	. . .	125	. . .	80	10	. . .	75	**269-321**
850-550-10	850	. . .	550	. . .	10	100	. . .	**269-321**
150-100-7	. . .	150	. . .	100	7	. . .	60	**302-363**
1050-700-7	1050	. . .	700	. . .	7	80	. . .	**302-363**
175-125-4	. . .	175	. . .	125	4	. . .	45	**341-444**
1200-850-4	1200	. . .	850	. . .	4	60	. . .	**341-444**
200-155-1	. . .	200	. . .	155	1	. . .	25	**388-477**
1400-1100-1	1400	. . .	1100	. . .	1	35	. . .	**388-477**
230-185	. . .	230	. . .	185	(b)	. . .	(b)	**444-555**
1600-1300	**1600**	**. . .**	**1300**	**. . .**	**(b)**	**(b)**	**. . .**	**444-555**

(a) Unnotched Charpy bars tested at 72 ± 7 °F (22 ± 4 °C). The values in the table are a minimum for the average of the highest three test values of four tested samples.

(b) Elongation and impact requirements are not specified. Although grades 200-155-1, 1400-1100-1, 230-185, and 1600-1300 are primarily used for gear and wear resistance applications, grades 200-155-1 and 1400-1100-1 have applications where some sacrifice in wear resistance is acceptable in order to provide a limited amount of ductility and toughness.

(c) Hardness is not mandatory and is shown for information only.

Manufacture and Metallurgical Control

Greater metallurgical and process control is required in production of ductile iron than in production of other cast irons. Frequent chemical, mechanical, and metallurgical testing is needed to ensure that the required quality is maintained and that specifications are met.

Manufacture of high-quality ductile iron begins with careful selection of charge materials that will yield a relatively pure cast iron free of undesirable residual elements sometimes found in other cast irons. Carbon, manganese, silicon, phosphorus, and sulfur must be held at specified levels. Magnesium, cerium, and certain other elements must be controlled in order to attain the desired graphite shape and to offset the deleterious effects of subversive elements; elements such as antimony, lead, titanium, tellurium, bismuth, and zirconium interfere with the nodulizing process, and must be either eliminated or restricted to very low concentrations.

Reduction of the sulfur content to less than 0.02% is necessary prior to the nodulizing process; this can be accomplished through basic melting alone, by use of low-sulfur charge material, or desulfurization of the base metal before the magnesium-nodulizing alloy is added. If base sulfur is not so reduced, excessive amounts of costly nodulizing alloys will be required and melting efficiency will be impaired.

Graphite Shape and Distribution. There are three major types of nodulizing agents, all of which contain magnesium: unalloyed magnesium, nickel-base nodulizers, and magnesium-ferrosilicon nodulizers. Unalloyed magnesium has been added to molten iron as wire, ingots, or pellets; as briquets, in combination with sponge iron; or in the cellular pores of metallurgical coke. The method of introducing the alloy has varied from an open-ladle method (in which the alloy is placed at the bottom of the ladle and iron is poured rapidly over the alloy) to a pressure-container method (in which unalloyed magnesium is placed inside a container is rotated so that the iron flows over the magnesium). In all cases, magnesium is vaporized and the vapors travel through the molten iron, lowering the sulfur content, and promoting formation of spheroidal graphite.

Testing and Inspection. Various tests are used to control the processing of ductile iron, starting with analyses of raw materials and of the molten metal both before and after the nodulizing treatment. Rapid thermal-arrest methods are used to determine carbon, silicon, and carbon equivalence in the molten iron. Silicon content is also determined by thermoelectric and spectrometric techniques. Chill tests are used for production-line testing for silicon.

After the nodulizing step, a standard test coupon for microscopic examination should be poured from each batch of metal, as recommended by AFS and as specified in ASTM A395. One ear of the test coupon is broken off and polished to reveal graphite shape and distribution, plus matrix structure. These characteristics are evaluated by comparison with standard ASTM/AFS photomicrographs, and acceptance or rejection of castings is based on this comparison.

Tensile-test specimens are machined from separately cast keel blocks, Y blocks, or modified keel blocks, as described in ASTM A 395. If the terms of purchase require tensile specimens to be taken from castings, the part drawing must identify the area of the casting and the size of the test specimens. These terms also must be mutually acceptable to both producer and purchaser.

Hardness testing of production castings also is used to evaluate conformance to specified properties. Some standard specifications, such as SAE J434b, relate strength and hardness, as shown in Table 3.

Heat Treatment. When the properties desired are difficult to obtain in the as-cast metal, ductile iron can be heat treated. Heat-treated ductile iron usually has more uniform mechanical properties that as-cast ductile iron, particularly in casts with wide variations in section thickness.

Ductile iron castings of large or nonuniform cross section occasionally are stress relieved at 540 to 660 °C (1000 to 1100 °F), which reduces warping and distortion during subsequent machining. Mechanical properties of castings are essentially unchanged by the stress-relieving process.

Full ferritizing annealing produces grade 60-40-18 for applications requiring maximum impact resistance and ductility. This heat treatment usually involves heating to 900 °C (1650 °F) and holding, then cooling to about 700 °C (1300 °F) and holding, following by controlled cooling to near room temperature.

Subcritical annealing produces either grade 60-40-18 or grade 65-45-12 for applications requiring high toughness and ductility. Subcritical annealing is usually done by heating to 730 °C (1350 °F) and holding until a ferritic structure is obtained, followed by controlled cooling to near room temperature.

Normalizing and tempering produces pearlitic grade 100-70-03, which is widely used for applications requiring good strength and wear resistance. Casting are heated to about 900 °C (1650 °F), held there long enough to stabilize the structure, and rapidly cooled with a fan or air blast. Then the castings are reheated to 540 to 675 °C (1000 to 1250 °F), which provides both stress relief and control of final hardness.

Martensitic ductile iron (grade 120-90-02) is produced by heating to about 900 °C (1650 °F) and holding, then quenching in agitated oil. This treatment produces castings of the highest strength and best wear resistance. Stress relief and control of final hardness are accomplished by tempering at 510 to 565 °C (950 to 1050 °F).

Austempered ductile iron (see Table 4) requires a two-stage heat treatment. The first stage, austenitizing, requires heating to and holding at about 900 °C (1650 °F). This is followed by the second stage, which requires quenching and isothermally holding at the required austempering temperature, usually in a salt bath. The properties of ADI depend principally on austempering temperature and time, and typical austempering treatment fall into two categories:

- Heat to 875 to 925 °C (1605 to 1695 °F), hold for 2 to 4 h, quench in a salt bath at 400 to 450 °C (750 to 840 °F), hold for 1 to 6 h, and cool to room temperature
- The same as the previous method but hold for 1 to 6 h at 235 to 350 °C (455 to 660 °F)

The first treatment listed above would yield high ductility and high strength with medium hardness but a very good ability to work harden. The second treatment would yield very high strength with some ductility and a fairly high hardness.

Figure 3 compares the strength and ductility of as-cast ductile iron with ductile irons subjected to the heat treatments described above. Further information is found in the Section "Heat Treating" in this Handbook.

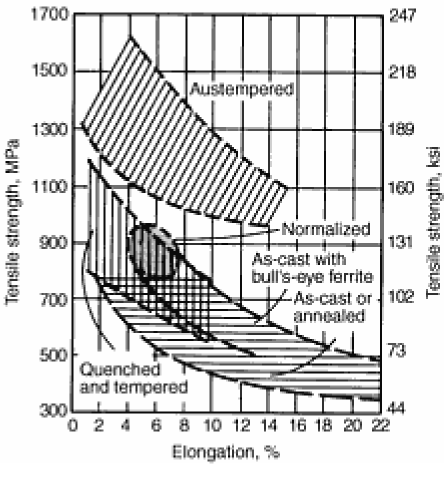


Fig. 3 Strength and ductility ranges of as-cast and heat-treated ductile irons

Mechanical Properties

Most of the standard specifications for ductile iron require minimum strength and ductility, as determined using separately cast standard ASTM test bars. The various specification limits have been established by evaluating the results from thousands of these test bars. Properties of test bars are useful approximations of the properties of finished castings. Test bar properties also make it possible to compare many different batches of metal without accounting for variations due to differences in the shapes being cast or differences in the production practices used in different foundries.

Test bars are machined from keel blocks, Y blocks, or modified keel blocks (see ASTM A 395 for details and dimensions). The test blocks are designed for ideal feeding from heavy molten metal heads over the mold and for controlled cooling at optimum rates. In practice, these characteristics may not be economically feasible, or may be impossible because of the configuration of the casting. As a result, actual properties of production castings may differ from those of test bars cast from the same heat of molten metal, a fact that sometimes is overlooked.

Effect of Composition. The properties of ductile iron depend first on composition. Composition should be uniform within each casting and among all castings poured from the same melt. Many elements influence casting properties, but those of greatest importance are the elements that exert powerful influences on matrix structure or on shape and distribution of graphite nodules.

Carbon influences the fluidity of the molten iron and the shrinkage characteristics of the cast metal, both of which affect casting design. Carbon also influences the size and number of graphite particles that are formed on solidification. The size and number of graphite particles is also influenced by inoculation procedures.

Silicon is a powerful graphitizing agent. Within the normal composition limits, increasing amounts of silicon promote structures that have progressively greater amounts of ferrite; furthermore, silicon contributes to the solution strengthening of ferrite. Increasing the amount of ferrite increases ductility and slightly increases yield strength, but concurrently reduces tensile strength and Brinell hardness.

Among the alloying elements commonly used to improve the mechanical properties of ductile iron, manganese acts as a pearlite stabilizer and increases strength, but reduces ductility. Nickel is frequently used to increase strength by promoting formation of fine pearlite. Nickel is also used to increase hardenability, especially for surface-hardening applications. Copper has been used as a pearlite stabilizer, and as such, increases strength. Molybdenum can be added to stabilize the structure at elevated temperature, thus promoting better retention of strength at temperatures up to about 650 °C (1200 °F) in unalloyed or low-alloy ductile irons.

Effect of Graphite Shape. Conversion of graphite from flakes to nodules, which is caused by addition of magnesium (or magnesium and cerium) to the molten iron, results in a fivefold to sevenfold increase in the strength of the cast metal. Shapes that are intermediate between a true nodular form and a flake form (such as, respectively, ASTM types I and VII, as established by ASTM A 247) yield mechanical properties that are inferior to those of ductile iron with a true nodular graphite but that are still better than the properties of gray iron of similar composition.

Effect of Section Size. Cooling rate is the variable chiefly affected by section size. The cooling rate, in turn, affects both the size of the graphite nodules and the microstructure of the matrix. The heavier the section, the more slowly it cools, and therefore, the larger the graphite nodules that can form on solidification. When ductile iron is cast in sections greater than about 65 mm ($2\frac{1}{2}$ in.), there is the possibility that degenerative graphite shapes (vermicular, crab, etc.) will be produced. Careful control of residual and/or the presence of small amounts of cerium are usually effective in combating this problem.

The structure of the matrix is essentially determined by the cooling rate through the eutectoid temperature range, although the specific effects of cooling rate are modified by the presence of alloying elements, as discussed previously in the section on effect of composition. Slow cooling rates prevalent in heavy sections promote transformation of ferrite. For a given silicon content, a decrease in section size and an increase in cooling rate tends to promote pearlite formation, along with an increase in strength and hardness and a decrease in ductility. Bainitic or martensitic structures are not often found in as-cast ductile iron, although it is possible for such structures to occur in very thin sections; these structures are normally obtained by heat treatment. Bainite and martensite are the main constituents in high-strength, heat-treated ductile irons such as grade 120-90-2.

Tensile properties of one heat of ductile iron heat treated to strength levels approximately equivalent to four standard ductile irons are given in Table 5. These values are not necessarily the average property values that can be expected for metal produced to the indicated grades. Within each grade. strength and ductility vary somewhat with hardness, as shown in Fig. 4. In some instances, the ranges of expected strength and ductility overlap those for the next higher or lower grade.

Table 5 Average mechanical properties of ductile irons heat treated to various strength levels

Nearest standard grade	Hardness, HB	Ultimate strength		Yield strength		Elongation in 50 mm (2 in.), %	Modulus		Poisson's ratio
		MPa	**ksi**	**MPa**	**ksi**		**GPa**	**10^6 psi**	
Tension									
60-40-18	167	461	66.9	329(a)	47.7(a)	15.0	169	24.5	0.29
65-45-12	167	464	67.3	332(a)	48.2(a)	15.0	168	24.4	0.29
80-55-06	192	559	81.1	362(a)	52.5(a)	11.2	168	24.4	0.31
120-90-02	331	974	141.3	864(a)	125.3(a)	1.5	164	23.8	0.28
Compression									
60-40-18	167	. . .	. . .	359(a)	52.0(a)	. . .	164	23.8	0.26
65-45-12	167	. . .	. . .	362(a)	52.5(a)	. . .	163	23.6	0.31
80-55-06	192	. . .	. . .	386(a)	56.0(a)	. . .	165	23.9	0.31
120-90-02	331	. . .	. . .	920(a)	133.5(a)	. . .	164	23.8	0.27
Torsion									
60-40-18	167	472	68.5	195(b)	28.3(b)	. . .	63 65.5(c)	9.1 9.5(c)	. . .
65-45-12	167	475	68.9	207(b)	30.0(b)	. . .	64 65(c)	9.3 9.4(c)	. . .
80-55-06	192	504	73.1	193(b)	28.0(b)	. . .	62 64(c)	9.0 9.3(c)	. . .
120-90-02	331	875	126.9	492(b)	71.3(b)	. . .	63.4 64(c)	9.2 9.3(c)	. . .

Note: Determined for a single heat of ductile iron, heat treated to approximate standard grades. Properties were obtained using test bars machined from 25 mm (1 in.) keel blocks.

(a) 0.2% offset.

(b) 0.0375% offset.

(c) Calculated from tensile modulus and Poisson's ratio in tension

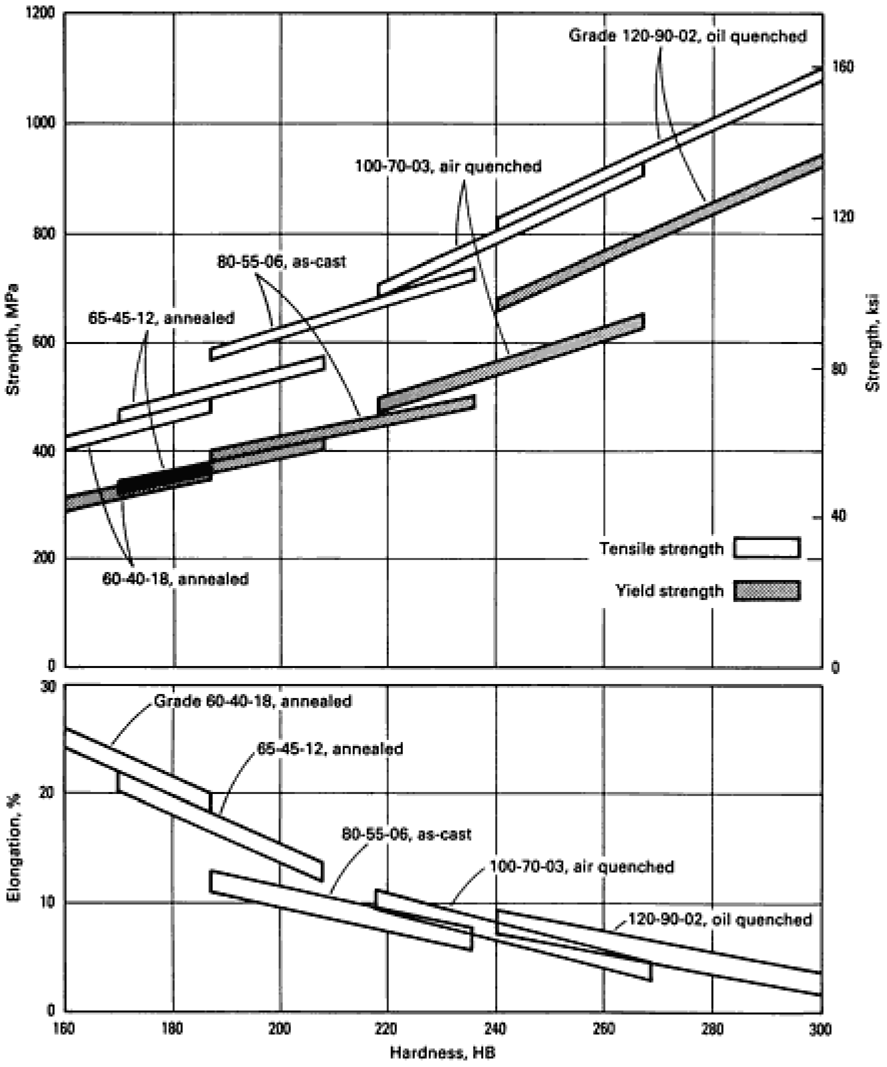


Fig. 4 Tensile properties of ductile iron versus hardness. Mechanical properties were determined on specimens taken from a 25 mm (1 in.) keel block.

As shown in Table 5, the modulus of elasticity in tension range from 164 to 169 GPa (23.8 to 24.5 × 10^6 psi) and does not vary greatly with grade. The values of tensile modulus shown in Table 5 were determined using standard 12.83 mm diameter (0.505 in. diameter) tensile bars equipped with strain gages affixed to the reduced section.

Compressive Properties. The 0.2% offset yield strength of ductile iron in compression generally is reported as 1.0 to 1.2 times the 0.2% offset yield strength in tension. The compressive properties shown in exit Table 5 were determined using specimens from the same single heat of ductile iron described previously above under "Tensile Properties."

Torsional Properties. Very few data are available on the ultimate shear strength of ductile iron because it is very difficult to obtain accurate shear data on materials that exhibit some ductility. It is generally agreed that the ultimate shear strength of ductile cast iron is about 0.9 to 1.0 times the ultimate tensile strength and 0.0375% offset yield strength in torsion for a single heat of ductile iron heat treated to strength levels approximately equivalent to four standard ductile irons.

Damping Capacity. The average damping capacity of ductile iron in the hardness range of 156 to 241 HB is about 6.6 times that of 1018 steel and about 0.12 times that of class 30 gray iron.

Impact Properties. Figure 5 shows data from a comprehensive study of impact properties of ductile iron. These data show that increasing pearlite decreases impact energy and that increasing phosphorus and/or silicone decreases impact energy. The transition temperature is significantly affected by phosphorus and/or silicon content, but is little affected by other elements present within the normal variations in composition.

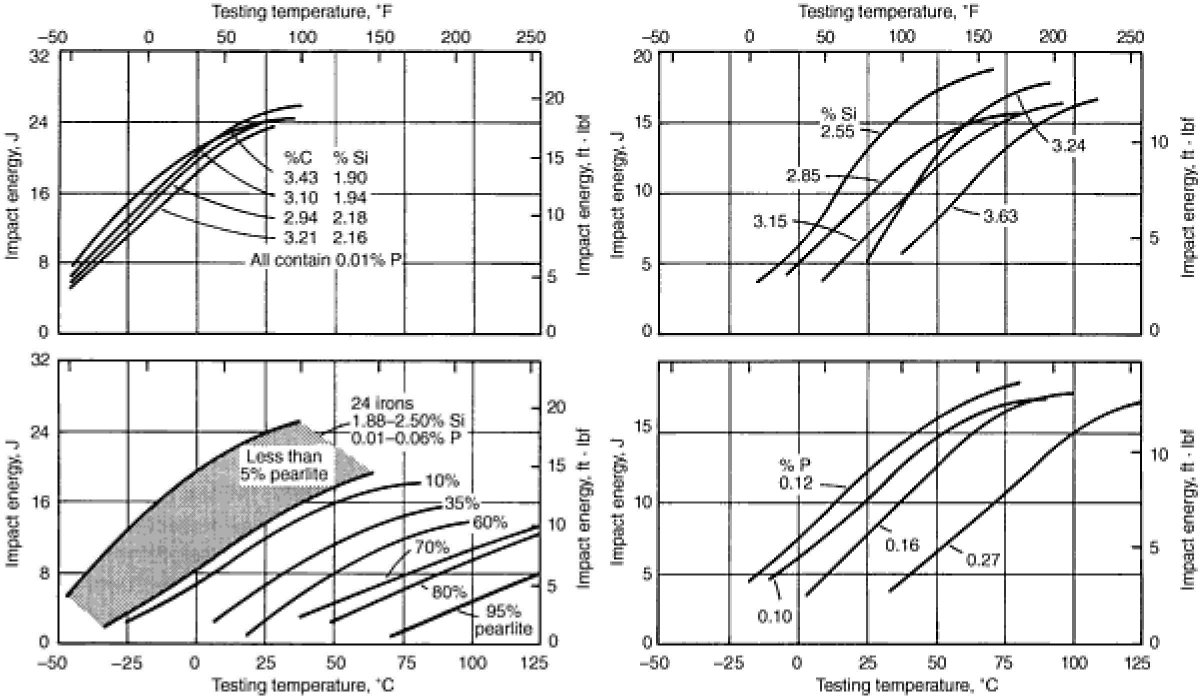


Fig. 5 Effect of composition and microstructure on Charpy V-notch impact behavior of ductile iron

Fracture Toughness. Certain low-strength grades of ductile iron do not fracture in a brittle manner when tested under nominal plane-strain conditions in a standard fracture toughness test. The behavior is contrary to the basic tenets of fracture mechanics and has been attributed to localized deformation in the ferrite envelope surrounding each graphite nodule. In the low-strength ductile irons, plane-strain conditions are established only at temperatures low enough to embrittle the ferrite. Otherwise, an increase in the size of the fracture toughness test specimens does not provide the degree of mechanical constraint necessary to obtain a valid measurement of K_{Ic}.

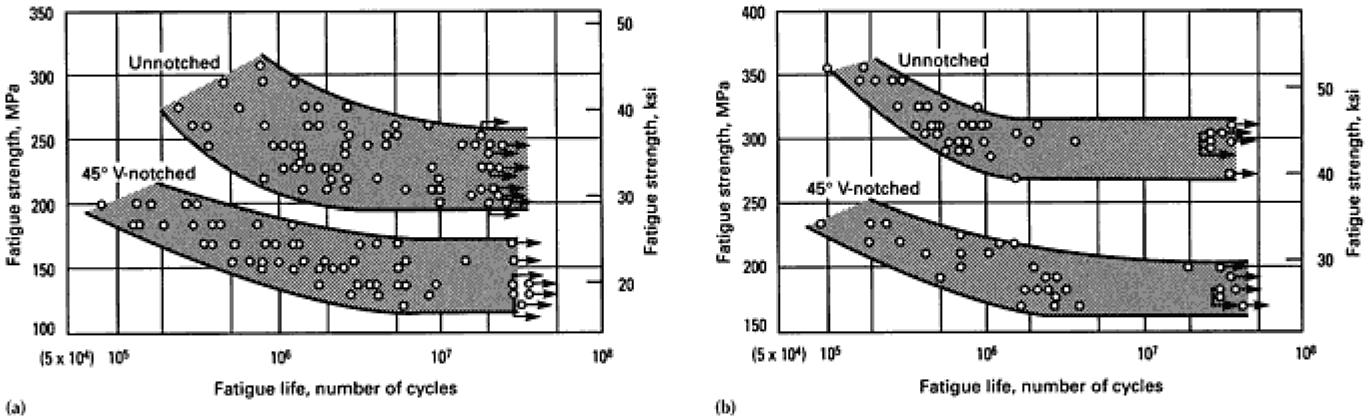
Table 6 gives selected values of fracture toughness. These values were determined using compact tension specimens 21 mm (0.83 in.) in width. All tests were completed in accordance with ASTM E 399. Table 6 gives data for ductile iron with a nodule shape approximately corresponding to 50% ASTM type I.

Table 6 Fracture toughness of ductile iron

Type of iron	Condition	Ultimate tensile strength		Yield strength		Elongation, %	K_{Ic},MPa · $m^{0.5}$ (ksi · in.$^{\frac{1}{2}}$) at:		
		MPa	**ksi**	**MPa**	**ksi**		**20 °C (70 °F)**	**-40 °C (-40 °F)**	**-105 °C (-160 °F)**
Ferritic 3.0% Si	As-cast	521	75.6	427	62.0	11.0	. . .	35.1 (32.0)	30.2 (27.5)
Ferritic 3.5% Si	As-cast	547	79.4	471	68.3	9.0	. . .	27.0 (24.6)	. . .
Pearlitic 2.5% Si	As-cast	703	102.0	374	54.2	7.5	. . .	37.1 (33.8)	. . .
	Normalized	918	133.2	552	80.0	3.6	45.3 (41.3)	. . .	. . .
	Austempered	. . .	. . .	620	90.0[(a)]	. . .	36.5 (33.3)	. . .	. . .

(a) Estimated

Fatigue Strength. Figure 6 shows fatigue-strength curves for ferritic and pearlitic ductile iron in both the notched and unnotched conditions. The tests were made on Wohler-type fatigue machines with polished specimens 10.6 mm (0.417 in.) in diameter.



Grade	Tensile strength		Unnotched			Notched			Stress concentration factor
			Endurance limit		**Endurance ratio**	**Endurance limit**		**Endurance ratio**	
	MPa	**ksi**	**MPa**	**ksi**		**MPa**	**ksi**		

60-40-18	480	70	205	30	0.43	125	18	0.26	1.67
80-55-06	680	99	275	40	0.40	165	24	0.24	1.67

Fig. 6 Fatigue strength versus fatigue life for ductile iron in both the unnotched and 45° Charpy V-notched condition. (a) Ferritic (60-40-18 annealed). (b) Pearlitic (80-55-06 as-cast)

The endurance limit for a given grade of ductile iron depends on surface conditions. Endurance ratio is defined as endurance limit divided by tensile strength. Because the endurance ratio of ductile iron declines as tensile strength increases, regardless of matrix structure, there may be little value in specifying a higher-strength ductile iron for a structure that is prone to fatigue failure; redesigning the structure to reduce stresses may prove to be a better solution.

Elevated-Temperature Properties

Ductile irons exhibit several properties that enable them to perform successfully in numerous elevated-temperature applications. Unalloyed grades retain their strength to moderate temperatures and exhibit significantly better resistance to dimensional growth and oxidation than unalloyed gray iron. High-alloy ductile irons (Ni-Resists) provide outstanding resistance to deformation, growth, and oxidation at high temperatures.

Compacted Graphite Iron

Introduction

COMPACTED GRAPHITE (CG) IRONS are the newest member of the cast iron family. Compacted graphite irons have inadvertently been produced in the past as a result of insufficient magnesium or cerium levels in melts intended to produce spheroidal graphite iron; however, it has only been since 1965 that CG iron has occupied its place in the cast iron family as a material with distinct properties requiring distinct manufacturing technologies.

Graphite Morphology

The shape of compacted graphite is rather complex. An acceptable CG iron is an iron in which there is no flake graphite in the structure and for which the amount of spheroidal graphite is less than 20%; that is, 80% of all graphite is compacted (vermicular) (ASTM A 247, Type IV). Figure 1 shows typical CG iron microstructures. It can be seen that although the two-dimensional appearance of compacted graphite is that of flakes with a length-to thickness ratio of 2 to 10 (Fig. 1a), the three-dimensional scanning electron microscopy (SEM) structure (Fig. 1b) shows that graphite does not appear in flakes but rather in clusters interconnected with the eutectic cell.

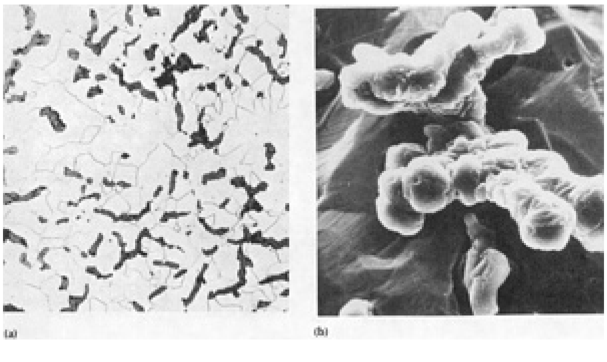


Fig. 1 Typical microstructures of CG irons. (a) Optical micrograph. Etched with nital. (b) SEM micrograph

showing true shape of graphite in CG iron. Full deep etch. 395×

This graphite morphology allows better use of the matrix, yielding higher strength and ductility than gray irons containing flake graphite. Similarities between the solidification patterns of flake and compacted graphite iron explain the good castability of the compacted graphite iron compared to that of ductile iron. In addition, the interconnected graphite provides better thermal conductivity and damping capacity than spheroidal graphite.

Chemical Composition

Carbon Equivalent. The characteristic properties of CG irons have been demonstrated over a rather wide range of carbon equivalent, CE, values, extending from hypoeutectic (CE = 3.7) to hypoeutectic (CE = 4.7), with carbon contents of 3.1 to 4.0% and silicon in amounts of 1.7 to 3.0%. At constant silicon levels, a lower CE slightly increases the chilling tendency and results in lower nodularity. At constant CE, higher silicon increases nodularitiy. Figure 2 shows the optimum carbon and silicon content.

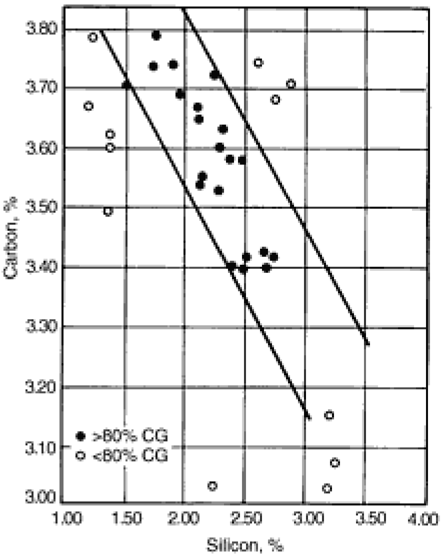


Fig. 2 Optimum range for carbon and silicon contents for CG iron

The optimum CE must be selected as a function of section size. For a given section size, too high a CE will result in graphite flotation, as in the case of spheroidal graphite cast iron, while too low a CE may result in increasing chilling tendency. For wall thicknesses ranging from 10 to 40 mm (0.4 to 1.6 in.), eutectic composition (CE = 4.3) is recommended in order to obtain optimum casting properties.

Manganese and Phosphorus Contents. The manganese content of CG iron can vary between 0.9 and 0.6%, depending on whether a ferritic or pearlitic structure is desired. The phosphorus content should be less than 0.06% to obtain maximum ductility from the matrix.

Sulfur Content. Although CG iron has been produced from base irons having sulfur contents as high as 0.07 to 0.12%, it is probably more economical to desulfurize the iron to a level of 0.01 to 0.025% before liquid treatment. The higher the sulfur content, the more alloy is required for melt treatment. Also, the risk of missing the composition window for CG iron is increased, because the residual treatment elements must be balanced with the residual sulfur. Typical residual sulfur levels after treatment are 0.01 to 0.02%.

Melt Treatment Elements. The change in graphite morphology from the flake graphite in the base iron to the compacted graphite in the final iron is achieved by liquid treatment with different iron elements. Those elements may include one or more of the following: magnesium, rare earths (cerium, lanthanum, praseodymium, etc.), calcium, titanium, and aluminum. The amount and combination to be used are a function of the method of liquid treatment (level of minor elements), base and sulfur, and section thickness.

Alloying elements, such as copper, tin, molybdenum, and even aluminum, can be used to change the as-cast matrix of CG iron from ferrite to pearlite. Typical ranges are 0.48 to 0.9% Cu, 0.033 to 0.13% Sn, and 0.5 to 1% Mo.

Properties and Applications

Properties. In general, the property values of CG irons (both mechanical and physical) fall between those of gray irons and ductile irons. Compared to gray irons, CG irons have certain advantages:

- Higher tensile strength at the same carbon equivalent, which reduces the need for expensive alloying elements such as nickel, chromium, copper and molybdenum
- Higher ratio of tensile strength to hardness
- Much higher ductility and toughness, which result in a higher safety margin against fracture
- Lower oxidation and growth at high temperatures
- Less section sensitivity for heavy sections

Compared to ductile irons, the advantages of CG irons are:

- Lower coefficient of thermal expansion
- Higher thermal conductivity
- Better resistance to thermal shock
- Higher damping capacity
- Better castability, leading to higher casting yield and the capability of pouring more intricate castings
- Improved machinability

Table 1 compares selected properties of gray, ductile, and CG irons. A listing of tensile properties of various CG irons produced by different melt treatment methods is given in Table 2. Table 3 lists property requirements of CG irons per ASTM A 842.

Table 1 Comparison of properties of cerium-treated CG iron with flake graphite (FG) iron of the same chemical composition, high-strength pearlitic FG iron, and ferritic spheroidal graphite (SG) iron in the as-cast condition

Property	High-strength pearlitic FG iron (100% pearlite, 100% FG)[(a)]	FG iron (100% pearlite, 100% FG)[(b)]	Ce-treated CG iron (>95%ferrite, >95% CG)[(b)]	SG iron (100% ferrite, 80% SG, 20% poor SG)[(b)]
Chemical composition, %	3.10 C, 2.10 Si, 0.60 Mn	3.61 C, 2.49 Si, 0.05 Mn	36.1 C, 2.54 Si, 0.05 Mn	3.56 C, 2.72 Si, 0.05 Mn
Tensile strength, MPa (ksi)	317 (46)	110 (16)	336 (48.7)	438 (63.5)
0.2% proof stress, MPa (ksi)	. . .	. . .	257 (37.3)	285 (41.3)
Elongation, %	. . .	. . .	6.7	25.3

Modulus of elasticity, GPa (10^6 psi)	108 (15.7)	96.9 (14.05)	158 (22.9)	176 (25.5)
Brinell hardness, HB	200	156	150	159
Charpy V-notched-bar impact toughness, J (ft · lbf)				
at 20 °C (68 °F)	. . .	. . .	9.32 (6.87)	24.5 (18.1)
at -20 °C (-4 °F)	. . .	. . .	6.57 (4.85)	9.81 (7.23)
at -40 °C (-40 °F)	. . .	. . .	7.07 (5.21)	6.18 (4.56)
Charpy impact bend toughness, J (ft · lbf)				
at 20 °C (68 °F)	4.9	2.0	32.07 (23.7)	176.5 (130.2)
at -20 °C (-4 °F)	. . .	. . .	26.48 (19.5)	148.1 (109.2)
at -40 °C (-40 °F)	. . .	. . .	26.67 (19.7)	121.6 (89.7)
Rotating-bar fatigue strength, MPa (ksi)	127.5 (18.5)	49.0 (7.1)	210.8 (30.6)	250.0 (36.3)
Thermal conductivity, W/(cm · K)	0.419	0.423	0.356	0.327

(a) Mechanical properties determined from a sample with a section size 30 mm (1.2 in.) in diameter.

(b) Mechanical properties determined from a Y block 23 mm (0.9 in.) section

Table 2 Tensile properties, hardness, and thermal conductivity of various CG irons at room temperature

Structural condition[a]	Graphite type	Tensile strength		0.2% proof stress		Elongation, %
		MPa	**ksi**	**MPa**	**ksi**	
Irons treated with additions of cerium						
As-cast ferrite (>95% F)	95% CG, 5% SG	336	48.7	257	37.3	6.7
Ferritic-pearlitic (>5% P)	95% CG, 5% SG	298	43.2	224	32.5	5.3

As-cast ferrite (90% F, 10% P)	85% CG, 15% SG	371	53.8	267	38.7	5.5
100% ferrite	85% CG, 15% SG	338	49.0	245	35.5	8.0
100% ferrite	CG	365 ± 63	53 ± 9	278 ± 42	40 ± 6	7.2 ± 4.5
Ferritic-pearlitic (>90% F, <10% P)	>90% CG	300-400	43-58	250-300	36-43	3-7
Ferritic-pearlitic (85% F)	70% CG, 30% SG	320	46.4	242	35	3.5
Pearlitic (90% P, 10% F)	90% CG	400-550	58-80	320-430	46-62	0.5-1.5
Pearlitic (95% P, 5% F)	80% CG, 20% SG	410	59.5	338	49	1
Irons treated with combinations of Mg + Ti (+Ce)						
As-cast ferrite (0.04% Ce, <0.01% Mg, 0.28% Ti)	95% CG, 5% SG	319	46.3	264	38.3	4
100% ferrite (annealed) (0.018% Mg, 0.089% Ti, 0.032% As)	CG	292	42.3	225	32.6	6
As-cast ferrite (0.017% Mg, 0.062% Ti, 0.036% As)	CG	380	55	272	39.4	2
As-cast ferrite (0.024% Mg, 0.084% Ti, 0.030% As)	CG	388	56.3	276	40	2.5
As-cast pearlite (0.016% Mg, 0.094% Ti, 0.067% As)	CG	414	60	297	43.1	2
As-cast pearlite (0.026% Mg, 0.083% Ti, 0.074% As)	CG + SG	473	68.6	335	48.6	2
As-cast pearlite (70% P, 30% F)	CG	386	56.0	278	40.3	2

(a) F, ferrite; P, pearlite

Table 3 Property requirements of CG irons per ASTM A 842

Grade[a]	Minimum tensile strength	Minimum yield strength	Elongation in 50 mm (2 in.), %	Hardness, HB	BID[b], mm

	MPa	**ksi**	**MPa**	**ksi**	(2 in.), %		
250[(c)]	250	36.3	175	25.4	3.0	179 max	4.50 min
300	300	43.5	210	30.5	1.5	143-207	5.0-4.2
350	350	50.8	245	35.5	1.0	163-229	4.7-4.0
400	400	58.0	280	40.6	1.0	197-255	4.3-3.8
450[(d)]	450	65.3	315	45.7	1.0	207-269	4.2-3.7

(a) Grades are specified according to the minimum tensile strength requirement given in MPa.

(b) Brinell impression diameter (BID) is the diameter (in mm) of the impression of a 10 mm diameter ball at a load of 3000 kgf.

(c) The 250 grade is a ferritic grade. Heat treatment to attain required mechanical properties and microstructure is the option of the manufacturer.

(d) The 450 grade is a pearlitic grade usually produced without heat treatment with addition of certain alloys to promote pearlite as a major part of the matrix.

Applications. Compacted graphite iron can be substituted for gray iron in all cases in which the strength of gray iron has become insufficient, but in which a change to SC iron is undesirable because of the less favorable casting properties of the SG iron. Examples include bed plates for large diesel engines, crankcases, gearbox housing, turbocharger housing, connecting forks, bearing brackets, pulleys for truck servodrives, sprocket wheels, and eccentric gears.

Because the thermal conductivity of CG iron is higher than that of ductile iron, CG iron is preferred for castings operating at elevated temperature and/or under thermal fatigue conditions. Applications include ingot molds, crankcases, cylinder heads, exhaust manifolds, and brake disks.

Malleable Iron

Introduction

MALLEABLE IRON is a type of cast iron that has most of its carbon in the form of irregularly shaped graphite nodules instead of flakes, as in gray iron, or small graphite spherulites, as in ductile iron. Malleable iron is produced by first casting the iron as a white iron and then heat treating the white cast iron to convert the iron carbide into the irregularly shaped nodules of graphite. This form of graphite in malleable iron is called temper carbon because it is formed in the solid state during heat treatment. Figure 1 shows the microstructure of typical malleable cast iron.

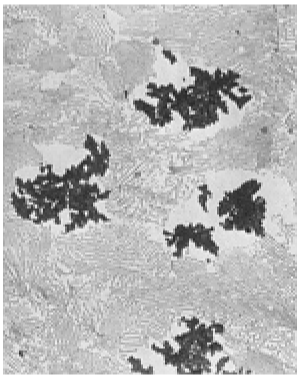


Fig. 1 Microstructure of a typical malleable cast iron showing graphite in the form of temper carbon. 4% picral etch. 250×

Malleable irons can be classified into three categories; ferritic malleable, pearlitic malleable, and martensitic malleable irons. There are two types of ferritic malleable iron, "blackheart," and "whiteheart." Only the blackheart type is produced in the United States. This material has a matrix of ferrite with interspersed nodules of temper carbon. "Cupola malleable iron" is a blackheart malleable iron produced by cupola melting and used for pipe fittings and similar thin-section castings. Because of its low strength and ductility, cupola malleable iron usually is not specified for structural applications. Pearlitic malleable iron is designed to have combined carbon in the matrix, resulting in higher strength and hardness than are available in ferritic malleable iron. Martensitic malleable iron is produced by quenching and tempering pearlitic malleable iron.

Malleable iron, like ductile iron, possesses considerable ductility and toughness because of its combination of nodular graphite and a low-carbon metallic matrix. Consequently, malleable iron and ductile iron are suitable for some of the same applications requiring good ductility and toughness and the choice between them is based on economy rather than properties. However, because ductile iron castings have similar properties to malleable iron castings, and do not require the long and expensive heat treatment, malleable iron production has fallen to very low levels, and only a few thin section castings are made this way today. Because solidification of white iron throughout a section is essential in the production of malleable iron, ductile iron also has a clear advantage when the section is too thick to permit solidification as white iron. Malleable iron castings are produced in section thicknesses ranging from about 1.5 to 100 mm ($\frac{1}{16}$ to 4 in.) and in weight from less than 30 g (1 oz) to 180 kg (400 lb) or more.

Metallurgical Control

The desired formation of temper carbon in malleable irons has two basic requirements: graphite should not form during the solidification of white cast iron, and graphite must be readily formed during the annealing heat treatment. These metallurgical requirements influence the useful compositions of malleable irons and the melting, solidification, and annealing procedures. Metallurgical control is based on the following criteria:

- Produce solidified white iron throughout the section thickness.
- Anneal on an established time-temperature cycle set to minimum values in the interest of economy.
- Produce the desired graphite distribution (nodule count) upon annealing.

Changes in melting practice or composition that would satisfy the first requirement listed above are generally opposed to satisfaction of the second and third requirement, while attempts to improve annealability beyond a certain point may result in an unacceptable tendency for the as-cast iron to be mottled instead of white.

Composition. Because of the two metallurgical requirements described above, malleable irons involve a limited range of chemical composition and the restricted use of alloys. The chemical composition of malleable iron generally conforms to the range given in Table 1.

Table 1 Typical compositions for malleable iron

Element	Composition, %	
	Ferritic	**Pearlitic**
Total carbon	2.2-2.9	2.0-2.9
Silicon	0.9-1.9	0.9-1.9
Manganese	0.2-0.6	0.2-1.3
Sulfur	0.02-0.2	0.05-0.2
Phosphorus	0.02-0.2	0.02-0.2

The common elements in malleable iron are generally controlled within about ±0.05 to ±0.15%. A limiting minimum carbon content is required in the interest of mechanical quality and annealability, because decreasing carbon content reduces the fluidity of the molten iron, increases shrinkage during solidification, and reduces annealability. A limiting maximum carbon content is imposed by the requirement that the casting be white as cast. The range in silicon content is limited to ensure proper annealing during a short-cycle, high-production annealing process and to avoid the formation of primary graphite (known as mottle) during solidification of the white iron. Manganese and sulfur contents are balanced to ensure that all sulfur is combined with manganese and that only a safe, minimum quantity of excess manganese is present in the iron. An excess of either sulfur or manganese will retard annealing in the second stage and therefore increase annealing costs.

In addition to the common elements listed in Table 1, malleable irons also contain some minor elements that are added as ladle additions. These include boron (<0.004%) and aluminum (0.005%), which promote graphitization during annealing, and bismuth (0.01%) and tellurium (<0.004%), which retard mottling.

Heat treatment is a two-stage process. In the first stage, the carbon is precipitated, and in the second stage the structure of the steel matrix is obtained. The first stage treatment is carried out at temperatures of 900 to 970 °C (1650 to 1780 °F) for 3 to 6 h, depending on the section size and composition. During this period iron carbide transforms to graphite. Higher temperatures can be used and will shorten the annealing time and increase nodule count; however, as the annealing temperature increases, the chance of casting distortion on cooling also increases. The number of graphite nodules produced depend on the carbon and silicon content, and generally should be between 80 and 150 mm^2 at 100× magnification for optimum properties.

To produce ferritic malleable iron, in which the matrix is ferritic, the castings are cooled to 740 to 760 °C (1650 to 1780 °F), a process that takes from 1 to 6 h, depending on the casting configuration. The castings are then cooled at the rate of 3 to 11 °C (5 to 20 °F) per h. As the castings cool, the carbon in the matrix diffuses to the temper carbon nodules, leaving a ferritic matrix.

In the production of pearlitic malleable, the first stage graphitization step is the same as that used for ferritic iron. However, at the end of the first stage, the castings are slowly cooled to around 870 °C (1600 °F) and rapidly cooled in air (which is blasted at the castings) or oil and then tempered (held for a period of time at a lower temperature) between 590 to 725 °C (100 to 1340 °F) according to specifications.

Microstructure / Property Relationships. The mechanical properties of malleable iron are dominated by matrix microstructure, so the mechanical properties may relate quite well to the relative hardness levels of different matrix microstructures. This general effect of microstructure on malleable irons is similar to that of many other steels and irons. The softer ferritic matrix provides maximum ductility with lower strength, while increasing the amount of pearlite increases hardness and strength but decreases ductility. Martensite provides further increases in hardness and strength but with additional decreases in ductility.

Ferritic Malleable Iron

Because ferritic malleable iron consists of only ferrite and temper carbon, the properties of ferritic malleable castings depend on the quantity, size, shape, and distribution of temper carbon and on the composition of the ferrite. Fully annealed ferritic malleable iron castings generally contain 2.00 to 2.70% graphite carbon by weight, which is equivalent to approximately 6 to 8% by volume. Because the graphite carbon contributes nothing to the strength of the castings, those with the lesser amount of graphite are somewhat stronger and more ductile than those containing the greater amount (assuming equal size and distribution of graphite particles). Elements such as silicon and manganese in solid solution in the ferritic matrix contribute to the strength and reduce the elongation of the ferrite. Therefore, by varying base metal composition, it is possible to obtain slightly different strength levels in a fully annealed ferritic product.

Table 2 Specifications and applications related to malleable iron castings

Specification No.	Class or grade(a)	ASTM metric equivalent class(b)	Microstructure	Typical applications
Ferritic				
ASTM A 47(c)	32510	22010	Temper carbon and ferrite	General engineering service at normal and elevated temperatures for good machinability and excellent shock resistance
ASTM A 338	(d)	. . .	Temper carbon and ferrite	Flanges, pipe fittings, and valve parts for railroad, marine, and other heavy-duty service to 345 °C (650 °F)
ASTM A 197/A 197M	(e)	. . .	Free of primary graphite	Pipe fittings and valve parts for pressure service
Pearlitic and martensitic				
ASTM A 220(c)	40010	280M10	Temper carbon in necessary matrix without primary cementite or graphite	General engineering service at normal and elevated temperatures. Dimensional tolerance range for castings is stipulated.
	45008	310M8		
	45006	310M6		
	50005	340M5		
	60004	410M4		
	70003	480M3		
	80002	550M2		

	90001	620M1		
Automotive				
ASTM A 602, SAE J158	M3210	. . .	Ferritic	For low-stress parts requiring good machinability: steering-gear housings, carriers, and mounting brackets
	M4504	. . .	Ferrite and tempered pearlite(f)	Compressor crankshafts and hubs
	M5003	. . .	Ferrite and tempered pearlite(f)	For selective hardening: planet carriers, transmission gears, and differential cases
	M5503	. . .	Tempered martensite	For machinability and improved response to induction hardening
	M7002	. . .	Tempered martensite	For high-strength parts: connecting rods and universal-joint yokes
	M8501	. . .	Tempered martensite	For high strength plus good wear resistance: certain gears

Mechanical properties are given in Table 3.

(a) First three digits of grade designation indicate the minimum yield strength (×100 psi); last two digits indicate minimum elongation (%).

(b) ASTM specifications designated by footnote (c) provide a metric equivalent class where the first three digits indicate minimum yield strength in MPa.

(c) Specifications with a suffix "M" utilize the metric equivalent class designation.

(d) Zinc-coated malleable iron specified per ASTM A 47.

(e) Cupola ferritic malleable iron.

(f) May be all tempered martensite for some applications

Specifications. Ferritic malleable iron is produced to one of three existing grades, depending on the melting practice employed and the applicable ASTM specification for the casting. See the listing under ASTM A 47, A 197, and A 602, grade M3210 in Tables 2 and 3.

Table 3 Properties of malleable iron castings

Specification No.	Class or grade	Tensile strength	Yield strength	Hardness, HB	Elongation(a), %

	grade	MPa	ksi	MPa	ksi	HB	%
Ferritic							
ASTM A 47/A47M and A 338	32510	340	50	220	32.5	156 max	10
ASTM A 197	. . .	276	40	207	30	156 max	5
Pearlitic and martensitic							
ASTM A 220/A 220M	40010	400	60	276	40	149-197	10
	45008	450	65	310	45	156-197	8
	45006	450	65	310	45	156-207	6
	50005	480	70	345	50	179-229	5
	60004	550	80	414	60	197-241	4
	70003	590	85	483	70	217-269	3
	80002	655	95	552	80	241-285	2
	90001	720	105	621	90	269-321	1
Automotive							
ASTM A 602, SAE J158	M3210(b)	345	50	224	32	156 max	10
	M4504(c)	448	65	310	45	163-217	4
	M5003(c)	517	75	345	50	187-241	3
	M5503(d)	517	75	379	55	187-241	3
	M7002(d)	621	90	483	70	229-269	2
	M8501(d)	724	105	586	85	269-302	1

Microstructure and typical applications are given in Table 2.

(a) Minimum in 50 mm (2 in.).

(b) Annealed.

(c) Air-quenched and tempered.

(d) Liquid-quenched and tempered

The mechanical properties that are most important for design purposes are tensile strength, yield strength, modulus of elasticity, fatigue strength, and impact strength. Hardness can be considered an approximate indicator that the ferritizing anneal was complete. The hardness of ferritic malleable iron almost always ranges from 110 to 156 HB and is influenced by the total carbon and silicon contents. Table 3 lists typical properties of unmachined test bars of ferritic mallable iron.

Pearlitic and Martensitic Malleable Iron

Pearlitic and martensitic-pearlitic malleable irons can be produced with a wide variety of mechanical properties, depending on heat treatment, alloying, and melting practices. The lower-strength pearlitic malleable irons are often produced by air cooling the casting after the first-stage anneal, while the higher-strength (pearlitic-martensitic) malleable irons are made by liquid quenching after the first-stage anneal.

Specifications. Some specifications for pearlitic and martensitic malleable iron are based on grade designations that require certain minimum tensile, yield, and elongation values, with advisory Brinell hardnesses (see Tables 2 and 3). The hardnesses are termed "advisory" because the hardness ranges corresponding to the various grades overlap so much that hardness alone cannot ensure that a given casting meets the specification for a specific grade (see, e.g., ASTM A 220). Other specifications (e.g., ASTM A 602 and SAE J158) are based on required hardness ranges and microstructures, and tensile data are considered advisory.

The mechanical properties of pearlitic and martensitic malleable iron vary in a substantially linear relationship with Brinell hardness. In the low-hardness ranges, below about 207 HB, the properties of air-quenched and tempered pearlitic malleable are essentially the same as properties of oil-quenched and tempered martensitic malleable. This is because attaining the low hardnesses requires considerable coarsening of the matrix carbides and partial second-stage graphitization. Either an air-quenched pearlitic structure or an oil-quenched martensitic structure can be coarsened and decarburized to meet this hardness requirement.

At higher hardnesses, oil-quenched and tempered malleable iron has higher yield strength and elongation than air-quenched and tempered malleable iron because of greater uniformity of matrix structure and finer distribution of carbide particles. Oil-quenched and tempered pearlitic malleable irons produced commercially to harnesses as high as 321 HB (see Table 3), while the maximum hardness for high-production air-quenched and tempered pearlitic malleable iron is about 255 HB. The lower maximum hardness is applied to the air-quenched material because:

- Hardness upon air quenching normally does not exceed 321 HB and may be as low as 269 HB; therefore, attempts to temper to a hardness range above 255 HB produce nonuniform hardness and make the process control limits excessive.
- Very little structural alteration occurs during the tempering heat treatment to a higher hardness, and the resulting structure is more difficult to machine than an oil-quenched and tempered structure at the same hardness.
- There is only a slight improvement in other mechanical properties with increased hardness above 255 HB.

Because of these considerations, applications for air-quenched and tempered pearlitic malleable iron are usually those requiring moderate strength levels, with the higher-strength applications need the oil-quenched and tempered material.

Alloy Cast Irons

Introduction

ALLOY CAST IRONS are considered to be those casting alloys based on the Fe-C-Si system that contain one or more alloying elements intentionally added to enhance one or more useful properties. The addition of a small amount of a substance (e.g., ferrosilicon, cerium, or magnesium) that is used to control the size, shape, and/or distribution of graphite particles is termed inoculation rather than alloying. The quantities of material used for inoculation neither change the basic composition of the solidified iron nor alter the properties of individual constituents. Alloying elements, including silicon when it exceeds about 3%, are usually added to increase the strength, hardness, hardenability, or corrosion resistance of the basic iron, and they are often added in quantities sufficient to affect the occurrence, properties, or distribution of constituents in the microstructure.

In gray and ductile irons, small amounts of alloying elements such as chromium, molybdenum, or nickel are used primarily to achieve high strength or to ensure the attainment of a specified minimum strength in heavy sections. Otherwise, alloying elements are used almost exclusively to enhance resistance to abrasive wear or chemical corrosion or to extend service at elevated temperatures.

Types of Alloy Cast Irons

Alloy cast irons can be broadly classified as either graphite-free, high-alloy cast irons (white irons) or graphitic high-alloy cast irons (graphite-containing ductile or gray irons). Table 1 lists approximate ranges of alloy content for various types of alloy cast irons, which can be further classified as abrasion-resistant cast irons, corrosion-resistant cast irons, or heat-resistant cast irons. Individual alloys within each type are made to compositions in which the actual ranges of one or more of the alloying elements span only a portion of the listed ranges. The listed ranges serve only to identify the types of alloys used in specific kinds of applications.

Table 1 Ranges of alloy content for various types of alloy cast irons

Description	Composition, wt%[a]									Matrix structure, as-cast[c]
	TC[b]	**Mn**	**P**	**S**	**Si**	**Ni**	**Cr**	**Mo**	**Cu**	
Abrasion-resistant white irons										
Low-carbon white iron[d]	2.2-2.8	0.2-0.6	0.15	0.15	1.0-1.6	1.5	1.0	0.5	[e]	CP
High-carbon, low-silicon white iron	2.8-3.6	0.3-2.0	0.30	0.15	0.3-1.0	2.5	3.0	1.0	[e]	CP
Martensitic nickel-chromium iron	2.5-3.7	1.3	0.30	0.15	0.8	2.7-5.0	1.1-4.0	1.0	. . .	M, A
Martensitic nickel, high-chromium iron	2.5-3.6	1.3	0.10	0.15	1.0-2.2	5-7	7-11	1.0	. . .	M, A

Martensitic chromium-molybdenum iron	2.0-3.6	0.5-1.5	0.10	0.06	1.0	1.5	11-23	0.5-3.5	1.2	M, A
High-chromium iron	2.3-3.0	0.5-1.5	0.10	0.06	1.0	1.5	23-28	1.5	1.2	M
Corrosion-resistant irons										
High-silicon iron[f]	0.4-1.1	1.5	0.15	0.15	14-17	. . .	5.0	1.0	0.5	F
High-chromium iron	1.2-4.0	0.3-1.5	0.15	0.15	0.5-3.0	5.0	12-35	4.0	3.0	M, A
Nickel-chromium gray iron[g]	3.0	0.5-1.5	0.08	0.12	1.0-2.8	13.5-36	1.5-6.0	1.0	7.5	A
Nickel-chromium ductile iron[h]	3.0	0.7-4.5	0.08	0.12	1.0-3.0	18-36	1.0-5.5	1.0	. . .	A
High-resistant gray irons										
Medium-silicon iron[i]	1.6-2.5	0.4-0.8	0.30	0.10	4.0-7.0	. . .	. . .	. . .	. . .	F
Nickel-chromium iron[g]	1.8-3.0	0.4-1.5	0.15	0.15	1.0-2.75	13.5-36	1.8-6.0	1.0	7.5	A
Nickel-chromium-silicon iron[j]	1.8-2.6	0.4-1.0	0.10	0.10	5.0-6.0	13-43	1.8-5.5	1.0	10.0	A
High-aluminum iron	1.3-2.0	0.4-1.0	0.15	0.15	1.3-6.0	. . .	20-25 Al	. . .	. . .	F
Heat-resistant ductile irons										
Medium-silicon ductile iron	2.8-3.8	0.2-0.6	0.08	0.12	2.5-6.0	1.5	. . .	2.0	. . .	F
Nickel-chromium ductile iron[h]	3.0	0.7-2.4	0.08	0.12	1.75-5.5	18-36	1.75-3.5	1.0	. . .	A
Heat-resistant white irons										
Ferritic grade	1-2.5	0.3-1.5	. . .	. . .	0.5-2.5	. . .	30-35	. . .	. . .	F

Austenitic grade	1-2.0	0.3-1.5	. . .	. . .	0.5-2.5	10-15	15-30	. . .	. . .	A

(a) Where a single value is given rather than a range, that value is a maximum limit.

(b) Total carbon.

(c) CP, coarse pearlite; M, martensite; A, austenite; F, ferrite.

(d) Can be produced from a malleable iron-base composition.

(e) Copper can replace all or part of the nickel.

(f) Such as Duriron, Durichlor 51, Superchlor (ASTM A 518).

(g) Such as Ni-Resist austenitic iron (ASTM A 436).

(h) Such as Ni-Resist austenitic ductile iron (ASTM A 439).

(i) Such as Silal.

(j) Such as Nicrosilal

White cast irons, so named because of their characteristically white fracture surfaces, do not have any graphite in the microstructure. Instead, the carbon is present in the form of carbides, chiefly of the types Fe_3C and Cr_7C_3. Often, complex carbides are also present, such as $(Fe,Cr)_3C$ from additions of 3 to 5% Ni and 1.5 to 2.5% Cr, $(Cr,Fe)_7C_3$ from additions of 11 to 35% Cr, or those containing other carbide-forming elements.

White cast irons are usually very hard, which is the single property most responsible for their excellent resistance to abrasive wear. White iron can be produced either throughout the section (chiefly by adjusting the composition) or only partly inward from the surface (chiefly by casting against a chill). The latter iron is sometimes referred to as chilled iron to distinguish it from iron that is white throughout.

Chilled iron castings are produced by casting the molten metal against a metal or graphite chill resulting in a surface virtually free from graphitic carbon. In the production of chilled iron, the composition is selected so that only the surfaces cast against the chill will be free from graphitic carbon (Fig. 1). The more slowly cooled portions of the casting will be gray or mottled iron. The depth and hardness of the chilled portion can be controlled by adjusting the composition of the metal, the extent of inoculation, and the pouring temperature.

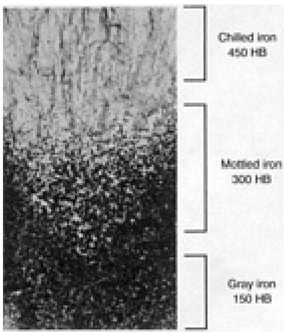


Fig. 1 Fracture surface of as-cast chilled iron. White, mottled, and gray portions are shown at full size, from top to bottom.

White iron is cast iron that is virtually free from graphitic carbon. The composition is chosen so that, for the desired section size, graphite does not form as the casting solidifies. The hardness of white iron castings can be controlled by adjustment of the composition.

The main difference between microstructure of chilled iron and white iron is that chilled iron is fine grained and exhibits directionality perpendicular to the chilled face, while white iron is ordinarily coarse grained, randomly oriented, and white throughout, even in relatively heavy sections. This difference reflects the composition difference between the two types of abrasion-resistant iron. Chilled iron is directional only because the casting, made of a composition that is ordinarily gray, has been cooled through the eutectic temperature so rapidly at one or more faces that the iron solidified white, growing inward from the chilled face. White iron, on the other hand, has a composition so low in CE or so high in alloy content that gray iron cannot be produced even at the relatively low rates of cooling that exist in the center of the heaviest section of the casting.

Corrosion-resistant irons derive their resistance to chemical attack chiefly from their high alloy content. Depending on which of three alloying elements dominates the composition (silicon up to 15%, chromium up to 28%, or nickel up to 35%) a corrosion-resistant iron can be ferritic, pearlitic, martensitic, or austenitic in its microstructure. Depending on composition, cooling rate, and inoculation practice, a corrosion-resistant iron can be white, gray, or nodular in both form and distribution of carbon.

Heat-resistant irons combine resistance to high-temperature oxidation and scaling with resistance to softening or microstructural degradation. Resistance to scaling depends chiefly on high alloy content, and resistance to softening depends on the initial microstructure plus the stability of the carbon-containing phase. Heat-resistant irons are usually ferritic or austenitic as-cast; carbon exists predominantly as graphite, either in flake or nodular form, which subdivides heat-resistant irons into either gray or ductile irons. There are also ferritic and austenitic white iron grades, although they are less frequently used and have no ASTM designations.

Effects of Alloying Elements

In most cast irons, it is the interaction between alloying elements (including carbon and silicon) that has the greatest effect on properties. This influence is exerted largely by effects on the amount and shape of graphitic carbon present in the casting. For example, depth of chill or the tendency of the iron to be white as cast depends greatly on the carbon equivalent and the balance between carbon and silicon in the composition; addition of other elements can only modify the basic tendency established by the carbon-silicon relationship.

In general, only small amounts of alloying elements are needed to improve depth of chill, hardness, and strength. Typical effects on depth of chill are given in Fig. 2 for the alloying elements commonly used in low to moderately alloyed cast irons. High-alloy contents are needed for the most significant improvements in corrosion resistance or elevated-temperature properties.

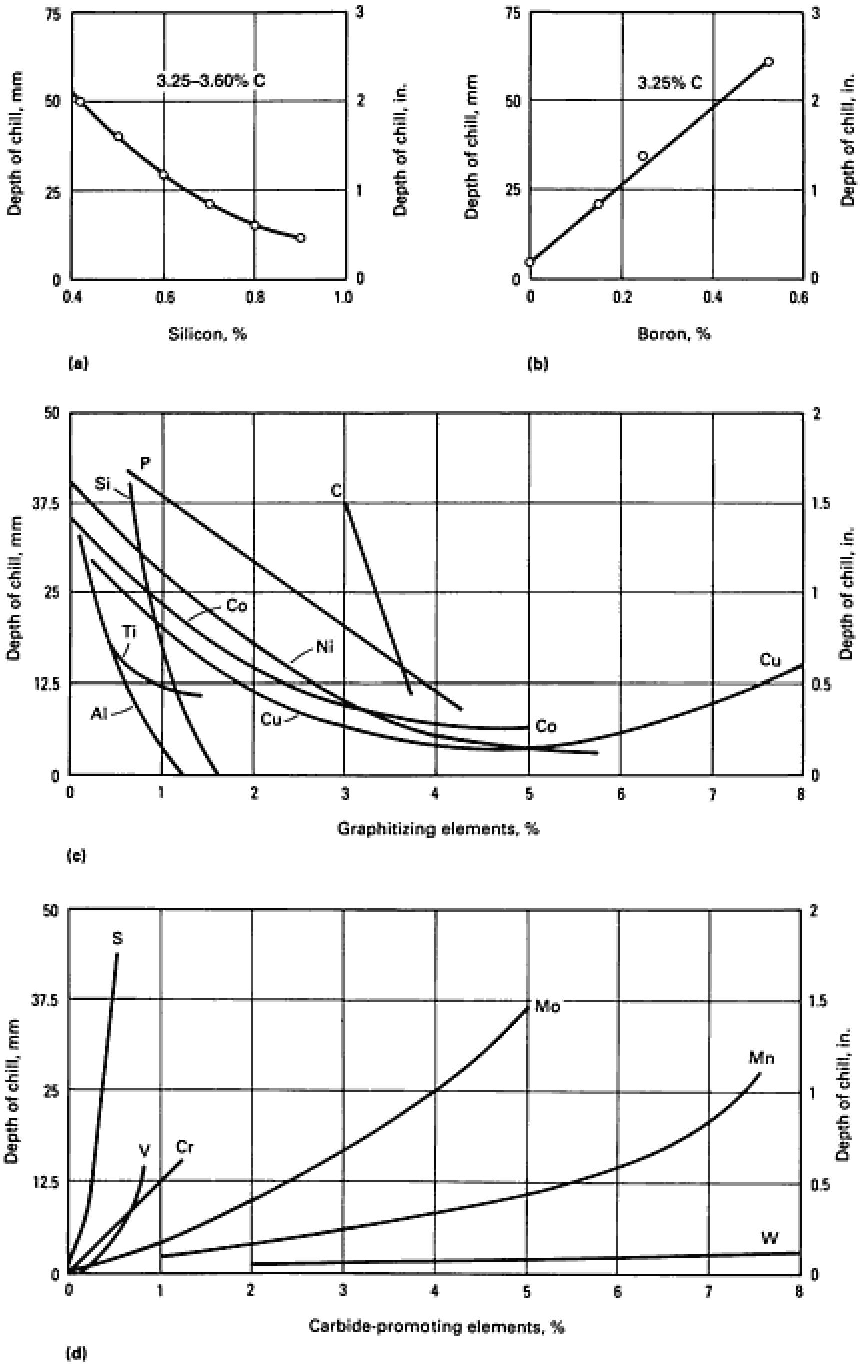


Fig. 2 Typical effects of alloying elements on depth of chill

Carbon. In chilled irons, the depth of chill decreases and the hardness of the chilled zone increases, with increasing carbon content (Fig. 2c). Carbon also increases the hardness of white irons.

Silicon is present in all cast irons. In alloy cast irons, as in other types, silicon is the chief factor that determines the carbon content of the eutectic. Increasing the silicon content lowers the carbon content of the eutectic and also promotes the formation of graphite on solidification. Thus, the silicon content is the principal factor controlling the depth of the chill in unalloyed or low-chromium chilled and white irons. Figure 2(a) summarizes this effect for relatively high-carbon irons.

Silicon additions of 4.5 to 8% improve high-temperature properties by raising the eutectoid transformation and by reducing the rates of scaling and growth. Additions of 14 to 17% Si (often accompanied by addition of about 5% Cr and

1% Mo) yield cast iron that is very resistant to corrosive acids, although resistance varies somewhat with acid concentration.

High-silicon irons are difficult to cast and are virtually unmachinable. High-silicon irons have particularly low resistance to mechanical and thermal shock at room temperature or moderately elevated temperature. However, above approximately 250 °C (500 °F), the shock resistance exceeds that of ordinary gray iron.

Manganese and sulfur should be considered together for their effects on gray or white iron. Alone, either manganese or sulfur increases the depth of chill, but when one element is present, addition of the other element decreases the depth of chill until the residual concentration is neutralized by the formation of manganese sulfide. Generally, sulfur is the residual element, and excess manganese can be used to increase chill depth and hardness, as shown in Fig. 2(d). Because it promotes formation of finer and harder pearlite, manganese is often used to decrease or prevent mottling in heavy-section castings.

Manganese, in excess of the amount needed to scavenge sulfur, mildly suppresses pearlite formation. It is also a relatively strong austenite stabilizer and normally is kept below ~0.7% in martensitic white irons. In some pearlitic or ferritic alloy cast irons, up to ~1.5% Mn can be used to help ensure that specified strength levels are obtained.

Phosphorus is a mild graphitizer in unalloyed irons; it mildly reduces chill depth in chilled irons (Fig. 2c). In alloyed irons, the effects of phosphorus are somewhat obscure. There is some evidence that it reduces the toughness of martensitic white irons.

Chromium has three major uses in cast irons: to form carbides, to impart corrosion resistance, and to stabilize the structure for high-temperature applications. Small amounts of chromium are added routinely to stabilize pearlite in gray iron, to control chill depth in chilled iron, or to ensure a graphite-free structure in white iron containing <1% silicon. At such low percentages, usually no greater than 2 to 3%, chromium has little or no effect on hardenability, chiefly because most of the chromium is tied up in carbides. However, chromium does influence the fineness and hardness of pearlite and also tends to increase the amount of hardness of the eutectic carbides.

When the chromium content of cast iron is greater than ~10%, eutectic carbides of the M_7C_3 type are formed, rather than the M_3C type that predominates at lower chromium contents. More significantly, however, the higher chromium content causes a change in solidification pattern to a structure in which the M_7C_3 carbides are surrounded by a matrix of austenite or its transformation products. At lower chromium contents, the M_3C carbide forms the matrix. Because of the solidification characteristics, hypoeutectic irons containing M_7C_3 carbides normally are stronger and tougher than irons containing M_3C carbides.

The relatively good abrasion resistance, toughness, and corrosion resistance found in high-chromium white irons have led to the development of a series of commercial martensitic or austenitic white irons containing 12 to 18% chromium. Because much of the chromium in these irons is present in combined form as carbides, chromium is much less effective than molybdenum, nickel, manganese, or copper in suppressing the eutectoid transformation to pearlite and thus has a lesser effect on hardenability than it has in steels. Martensitic white irons usually contain one or more of the elements molybdenum, nickel, manganese, and copper to give the required hardenability. These elements ensure that martensite will form on cooling from above the upper transformation temperature either while the casting is cooling in the mold or during subsequent heat treatment.

Nickel is almost entirely distributed in the austenite phase or its transformation products. Nickel tends to promote graphite formation, and in white and chilled irons, this effect usually is balanced by the addition of about one part chromium for every three parts nickel in the composition.

One of the Ni-Hard family of commercial alloy white irons (Type IV Ni Hard, also known as Class I Type D, Ni-HiCr in ASTM A 532) contains 1.0 to 2.2% Si, 5 to 7% Ni, and 7 to 11% Cr. In the as-cast condition, it has a structure of M_7C_3 eutectic carbides in a martensitic matrix. If retained austenite is present, the martensite content and hardness of the alloy can be increased by refrigeration treatment or by reaustenitizing and air cooling. Ni-Hard IV often is specified for pumps and other equipment used for handling abrasive slurries because of its combination of relatively good strength, toughness, and resistance to abrasion.

Nickel additions of >12% are needed for optimum resistance to corrosion or heat. High-nickel gray or ductile irons usually contain 1 to 6% chromium, and can contain as much as 10% copper. These elements act in conjunction with the nickel to promote resistance to corrosion and scaling, especially at elevated temperatures. All types of cast iron with nickel contain >18% are fully austenitic.

Copper in moderate amounts can be used to suppress pearlite formation in both low- and high-chromium martensitic white irons. It has a relatively mild effect compared with that of nickel, and, because of the limited solubility of copper in austenite, copper additions probably should be limited to ~2.5%. This limitation means that copper cannot completely replace nickel in Ni-Hard-type irons.

Copper is used in amounts of ~3 to 10% in some high-nickel gray and ductile irons that are specified for corrosion or high-temperature service. Here, copper enhances corrosion resistance, particularly resistance to oxidation or scaling.

Molybdenum in chilled and white iron compositions is distributed between the eutectic carbides and the matrix. In graphitic irons, the functions are to promote deep hardening and to improve corrosion resistance and high-temperature strength.

In chilled iron compositions, molybdenum additions mildly increase depth of chill (they are about one-third as effective as chromium; see Fig. 2d). The primary purpose of small additions (0.25 to 0.75%) of molybdenum to chilled iron is to improve the resistance of the chilled face to spalling, pitting, chipping, and heat checking. Molybdenum hardens and toughens the pearlitic matrix.

Where a martensitic white iron is desired for superior abrasion resistance, additions of 0.5 to 3.0% molybdenum effectively suppress formation of pearlite and other high-temperature transformation products when used in combination with copper, chromium, nickel, or both chromium and nickel.

Vanadium is a potent carbide stabilizer and increases depth of chill. The magnitude of the increase of depth of chill depends on the amount of vanadium and the composition of the iron, as well as on section size and conditions of castings. The powerful chilling effect of vanadium in thin sections can be balanced by additions of nickel of copper, or by a large increase in carbon or silicon, or both. In addition to carbide-stabilizing influence, vanadium in amounts of 0.10 to 0.50% refines the structure of the chill and minimizes coarse columnar grain structure.

Because of its strong carbide-forming tendency, vanadium is rarely used in gray or ductile irons for corrosion or elevated-temperature service.

Abrasion-Resistant Cast Irons

High-alloy white irons are used for abrasion-resistant applications in crushing, grinding, and materials handling. They usually contain substantial amounts of chromium, to stabilize the carbide, and to form chromium carbides, which are harder than iron carbide. Maximum hardness is found with a fully martensitic matrix. These irons fall into three categories:

- Nickel-chromium irons containing 3 to 5% Ni and 1 to 4% Cr, known by the trade name Ni-Hard. These are relatively low cost irons used primarily in mining operations as ball mill liners and grinding balls. They may also be used in slurry pumps and crusher segments. If moderate impact resistance is needed, the low-carbon version of the iron is used.
- Chromium-molybdenum irons, containing 11 to 23% Cr and up to 3% Mo, and some nickel and copper. These alloys provide the best combination of toughness and abrasion resistance of all white irons and are used in hard rock mining equipment, slurry pumps, coal grinding mills, and brick molds.
- High-chromium irons, containing 25 to 28% Cr and additions of molybdenum or nickel up to 1.5%. The high-chromium contents provide not only high hardness, but also corrosion resistance, and these irons are used in pumps for handling fly ash and in chloride-containing environments.

Hardness also increases as the carbon content increases, and silicon increases the temperature at which martensite (a very hard matrix structure produced by rapid quenching) forms, making heat treatment for martensitic alloy white irons easier. However, as higher carbon and silicon contents tend to promote graphite formation during solidification, they must be used in conjunction with alloying elements such as chromium to stabilize the carbide.

ASTM specification A 532 covers white iron grades used for abrasion-resistant applications. Table 2 lists the composition requirements for these alloys. Depending on the heat treatment carried out, hardness values ranging from 41 to 59 HRC can be achieved. Figure 3 shows typical microstructures encountered with these alloys.

Table 2 Compositions of abrasion-resistant white irons per ASTM A 532

Class	Type	Designation	Composition, wt%								
			C	**Mn**	**Si**	**Ni**	**Cr**	**Mo**	**Cu**	**P**	**S**
I	A	Ni-Cr-HiC	2.8-3.6	2.0 max	0.8 max	3.3-5.0	1.4-4.0	1.0 max	. . .	0.3 max	0.15 max
I	B	Ni-Cr-LoC	2.4-3.0	2.0 max	0.8 max	3.3-5.0	1.4-4.0	1.0 max	. . .	0.3 max	0.15 max
I	C	Ni-Cr-GB	2.5-3.7	2.0 max	0.8 max	4.0 max	1.0-2.5	1.0 max	. . .	0.3 max	0.15 max
I	D	Ni-HiCr	2.5-3.6	2.0 max	2.0 max	4.5-7.0	7.0-11.0	1.5 max	. . .	0.10 max	0.15 max
II	A	12% Cr	2.0-3.3	2.0 max	1.5 max	2.5 max	11.0-14.0	3.0 max	1.2 max	0.10 max	0.06 max
II	B	15% Cr-Mo	2.0-3.3	2.0 max	1.5 max	2.5 max	14.0-18.0	3.0 max	1.2 max	0.10 max	0.06 max
II	D	20% Cr-Mo	2.0-3.3	2.0 max	1.0-2.2	2.5 max	18.0-23.0	3.0 max	1.2 max	0.10 max	0.06 max

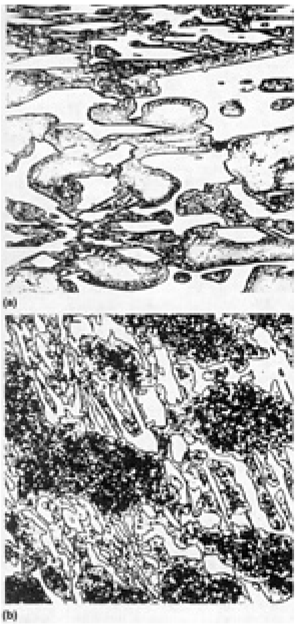


Fig. 3 High-chromium white iron microstructures. (a) As-cast austenitic-martensitic matrix microstructure. (b) Heat-treated martensitic microstructure. The massive carbides typically found in high-alloy white irons are the white constituent. Both at 500×

Corrosion-Resistant Cast Irons

The corrosion resistance of gray cast iron is enhanced by the addition of appreciable amounts of nickel, chromium, and copper, singly or in combination, or silicon in excess of about 3%. Table 1 gives chemical composition ranges for some of the more widely used corrosion-resistant cast irons.

Up to 3% silicon is normally present in all cast irons; in larger percentages, silicon is considered an alloying element. It promotes the formation of a strongly protective surface film under oxidizing conditions such as exposure to oxidizing acids. Relatively small amounts of molybdenum and/or chromium can be added in combination with high silicon. The addition of nickel to gray iron improves resistance to reducing acids and provides a high resistance to caustic alkalis. Chromium assists in forming a protective oxide that resists oxidizing acids, although it is of little benefit under reducing conditions. Copper has a smaller beneficial effect on resistance to sulfuric acid.

High-silicon irons are the most universally corrosion-resistant alloys available at moderate cost. They are widely used for handling corrosive media common in chemical plants, even when abrasive conditions also are encountered. When the silicon content is ≥14.2% these irons exhibit a very high resistance to boiling sulfuric acid.

The 14.5% Si iron is less resistant to the corrosive action of hydrochloric acid, but this resistance can be improved by additions of chromium and molybdenum and can be further enhanced by increasing the silicon content to 17%. The chromium-bearing silicon irons are very useful in contact with solutions containing copper salts, "free" wet chlorine, or other strongly oxidizing contaminants.

High-silicon irons, which are covered by ASTM specification A 518, have poor mechanical properties and particularly low thermal and mechanical shock resistance. These alloys are typically very hard and brittle with a tensile strength of about 110 MPa (16 ksi) and a hardness of 480 to 520 HB. They are difficult to cast and are virtually unmachinable.

High-chromium irons containing from 40 to 35% Cr give good service with oxidizing acids, particularly nitric, but are not resistant to reducing acids. These irons are also reliable for use in weak acids under oxidizing conditions, in numerous salt solutions, in organic acid solutions, and in marine or industrial atmospheres.

Heat-Resistant Cast Irons

Heat-resistant cast irons are basically alloys of iron, carbon, and silicon having high-temperature properties markedly improved by the addition of certain alloying elements, singly or in combination, principally chromium, nickel, molybdenum, aluminum, and silicon >3%. Silicon and chromium increase resistance to heavy scaling by forming a light surface oxide that is impervious to oxidizing atmospheres. Both elements reduce the toughness at elevated temperatures. Molybdenum also increases high-temperature strength. Aluminum additions reduce both growth and scaling but adversely affect mechanical properties at room temperature. Table 1 gives chemical composition ranges of some of the more widely used heat-resistant irons (both gray and ductile types) suitable for elevated-temperature service.

Growth is the permanent increase in volume that occurs in some cast irons after prolonged exposure to elevated temperature or after repeated cyclic heating and cooling. It is produced by the expansion that accompanies graphitization, expansion, and contraction at the transformation temperature and internal oxidation of the iron. Gases can penetrate the surface of hot cast iron at the graphite flakes and oxidize the graphite as well as the iron and silicon. The occurrence of fine cracks, or "crazing," may accompany repeated heating and cooling through the transformation temperature range because of thermal and transformational stresses.

Silicon contents of less than ~3.5% increase the rate of growth by promoting graphitization but silicon contents of ≥4% retard growth.

The carbide-stabilizing alloying elements, particularly chromium, effectively reduce growth in gray irons ≥450 °C (850 °F). Growth is not a problem at <400 °C (750 °F), except in the presence of superheated steam, where it can occur in coarse-grain irons at 310 °C (600 °F). Even small amounts of chromium, molybdenum, and vanadium produce marked reductions in growth at the higher temperatures.

Scaling. In addition to the internal oxidation that contributes to growth, a surface scale forms on unalloyed gray iron after exposure at a sufficiently high temperature.

Silicon, chromium, and aluminum increase the scaling resistance of cast iron by forming a light surface oxide that is impervious to oxidizing atmospheres. Unfortunately, these elements tend to reduce toughness and thermal shock resistance. The presence of nickel improves the scaling resistance of most alloys containing chromium and, more importantly, increases their toughness and strength at elevated temperatures. Carbon has a somewhat damaging effect at 700 °C (1300 °F) as a result of the mechanism of decarburization and the evolution of carbon monoxide and carbon dioxide. When these gases are evolved at the metal surface, the formation of protective oxide layers is hindered, and cracks and blisters can develop in the scale.

Figure 4 indicates the temperatures at which various silicon-chromium irons can be used with only slight or insignificant scaling in sulfur-free oxidizing atmospheres. Greater scaling rates can be tolerated in some applications, so that higher useful temperatures are often possible.

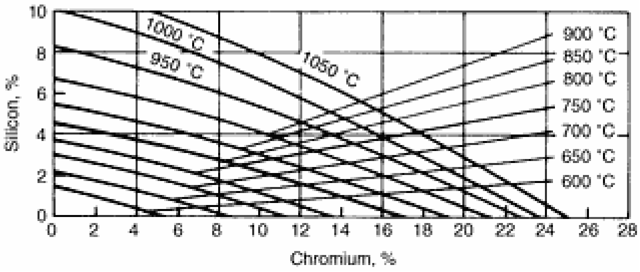


Fig. 4 Relation of silicon and chromium contents to the scaling resistance of silicon-chromium irons. Temperatures indicated at which various irons can be used with very little or insignificant scaling in sulfur-free oxidizing atmospheres

High-Nickel Irons. The austenitic cast irons containing 18 to 36% Ni, up to 7% Cu, and 1.75 to 4% Cr are used for both heat-resistant and corrosion-resistant applications. Known as Ni-Resist, this type of iron exhibits good resistance to high-temperature scaling and growth up to 815 °C (1500 °F) in most oxidizing atmospheres and good performance in steam service up to 530 °C (990 °F) can handle sour gases and liquids up to 400 °C (750 °F). The maximum use temperature is 540 °C (1000 °F) if appreciable sulfur is present in the atmosphere. Austenitic cast irons can be employed at temperatures as high as 950 °C (1740 °F). Austenitic irons have the advantage of considerably greater toughness and thermal shock resistance than the other heat-resistant alloy irons, although their strength is rather low.

High-nickel ductile irons are considerably stronger and tougher than the comparable gray irons. Tensile strengths of 400 to 470 MPa (58 to 68 ksi), yield strengths of 200 to 275 MPa (30 to 40 ksi), and elongations of 10 to 40% may be realized in high-nickel ductile irons. Tables 3 and 4 list compositions and properties, respectively, of austenitic ductile irons.

Table 3 Compositions of nodular-graphite (ductile) austenitic cast irons per ASTM A 439

Type	UNS No.	Composition, %					
		TC[a]	**Si**	**Mn**	**P**	**Ni**	**Cr**
D-2	F43000	3.00 max	1.50-3.00	0.70-1.25	0.08 max	18.0-22.0	1.75-2.75
D-2b	F43001	3.00 max	1.50-3.00	0.70-1.25	0.08 max	18.0-22.0	2.75-4.00
D-2c	F43002	2.90 max	1.00-3.00	1.80-2.40	0.08 max	21.0-24.0	0.50 max
D-3	F43003	2.60 max	1.00-2.80	1.00 max	0.08 max	28.0-32.0	2.50-3.50

D-3a	F43004	2.60 max	1.00-2.80	1.00 max	0.08 max	28.0-32.0	1.00-1.50
D-4	F43005	2.60 max	5.00-6.00	1.00 max	0.08 max	28.0-32.0	4.50-5.50
D-5	F43006	2.60 max	1.00-2.80	1.00 max	0.08 max	34.0-36.0	0.10 max
D-5b	F43007	2.40 max	1.00-2.80	1.00 max	0.08 max	34.0-36.0	2.00-3.00
D-5S	. . .	2.30 max	4.9-5.5	1.00 max	0.08 max	34.0-37.0	1.75-2.25

(a) Total carbon

Table 4 Typical mechanical properties of nodular-graphite austenitic cast irons per ASTM A 439

Type	Minimum tensile strength		Minimum yield strength		Minimum elonga-gation[(a)], %	Hardness, HB
	MPa	**ksi**	**MPa**	**ksi**		
D-2	400	58	205	30	8	139-202
D-2b	400	58	205	30	7	148-211
D-3	380	55	205	30	6	139-202
D-4	415	60	. . .	. . .	. . .	202-273
D-5	380	55	205	30	20	131-185

(a) In 50 mm (2 in.)

High-Silicon Irons. Graphitic irons alloyed with 4 to 6% Si provide good service and low cost in many elevated-temperature applications. These irons, whether gray or ductile, provide good oxidation resistance and stable ferritic matrix structures that will not go through a phase change at temperatures up to 900 °C (1650 °F).

Although quite brittle at room temperature, the high-silicon gray irons are reasonably tough at temperatures above 260 °C (500 °F). The ductile iron versions of these alloys have higher strength and ductility and are used for more rigorous service. Substantial improvements in yield and tensile strengths can be achieved in high-silicon ductile irons by alloying with molybdenum ($\leq$2.5% Mo).

High-Aluminum Irons. Alloy cast irons containing 6 to 7% Al, 18 to 25% Al, or 12 to 25% Cr plus 4 to 16% Al are reported to have considerably better resistance to scaling than several other alloy irons, including the high-silicon type. These high-aluminum irons have been used infrequently commercially because of their brittleness and poor castability.

Pressed-and-Sintered Ferrous Powder Metallurgy Parts

Introduction

IRON POWDERS are the most widely used powder metallurgy (P/M) material for structural parts. Nearly 90% of all iron and iron-base (ferrous) powder produced is used in P/M part applications, and the automotive industry is the leading powder user. Other important application areas include business machines, lawn and garden equipment, power tools, lock hardware, and appliances.

The single largest use of iron powders for nonstructural applications is coated and tubular electrodes for arc welding. Other nonstructural areas include pharmaceuticals and food enrichment (Americans consume about two million lb of iron powder annually in iron-enriched cereals and bread). Iron powder is also used as a carrier for toner in electrostatic copying machines.

This article will review low- to medium-density iron and low-alloy steel parts produced by pressing-and-sintering technology (a subsequent article in this Section reviews high-density ferrous parts produced by powder forging and injection molding). Manufacturing processes for pressed-and-sintered P/M parts consist of (1) powder production, cold compaction, and sintering, or (2) powder production, warm compaction, and sintering. By cold pressing and sintering only, parts are produced to density levels of about 6.4 to 7.1 g/cm^3, which is about 80 to 90% of theoretical density (the theoretical density of iron or low-carbon steel is about 7.87 g/cm^3). Warm compaction can increase density levels to 7.2 g/cm^3 to slightly more than 7.4 g/cm^3 (about 95% of theoretical density). High-temperature sintering also produces higher densities. Secondary processes, such as infiltration or double-pressing/double-sintering, can be used to increase densities to levels just below what are achievable with high-density processes. As shown in Fig. 1, however, higher costs are associated with secondary processing or high-density processing. As will be described below, higher densities correlate with improved mechanical properties.

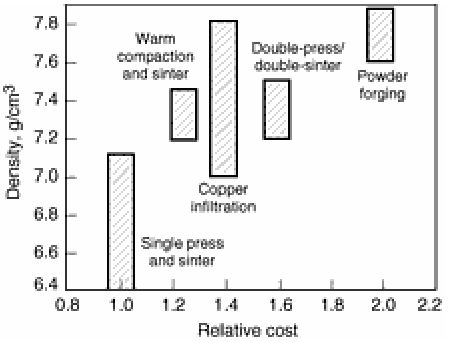


Fig. 1 Relative cost versus density of several P/M processes. Source: Hoeganaes Corporation

Powder Production

There are a number of commercial processes available for production of ferrous powders. Among these, the most important are direct reduction of oxides and atomization of liquid metal. Iron powders are also produced by carbonyl vapor metallurgy processing (carbonyl iron) and electrolysis (electrolytic iron).

Direct Reduction of Oxides

There are two commercially available processes for direct reduction of oxides: reduction with carbon (Hoeganaes process) and reduction with hydrogen (Pyron process). Generally, reduced iron powders are used for low- or medium-stress applications.

In the Hoeganaes process, sponge iron is produced by direct reduction of magnetite (Fe_3O_4) ore. Magnetite ore is dried in a rotary dryer and ground and cleaned with a magnetic separator. Cleaned ore is then charged into silicon carbide tubes with a crushed lime and coke mixture and heated at 1260 °C (2300 °F) for 24 to 40 hours in a tunnel kiln. Iron ore is reduced by carbon monoxide gas generated from the coke.

After removal from the kiln, the caked 25 mm (1 in.) diam sponge iron lumps undergo a series of grinding, screening, and magnetic separation steps to produce a powder of the desired particle size distribution. The cleaned powder is then charged into a strip belt furnace and annealed at about 870 °C (1600 °F) in an atmosphere of dissociated ammonia in order to reduce the carbon and oxygen levels. At the same time, strain hardening introduced during grinding is relieved. As shown in Fig. 2, the resultant powder has an irregular shape and is highly porous.

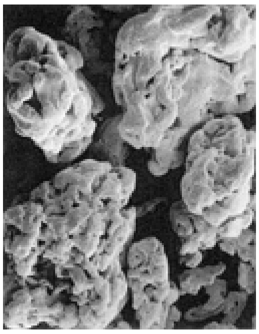


Fig. 2 Scanning electron micrograph of carbon-reduced iron ore shown at 180×

In the Pyron process, iron powder is produced by reducing selected iron oxides under a hydrogen atmosphere. In this process, mill scale is ground, magnetically separated, and screened. The mill scale is then preheated in air in order to convert all the oxides into hematite (Fe_2O_3), because hematite reduces more readily than magnetite (Fe_3O_4). The oxides are then reduced in a belt furnace under a hydrogen atmosphere at approximately 980 °C (1800 °F). The reduced iron is then ground, screened, and blended to specifications. No annealing step is necessary with the Pyron process.

Pyron iron powder has fine porosity and a spongelike microstructure (Fig. 3). The pores in the interior structure of Pyron iron powder particles are considerably finer than those in Hoeganaes sponge iron powder particles because in the latter the long-term reducing treatment at higher temperature coarsens the pores.

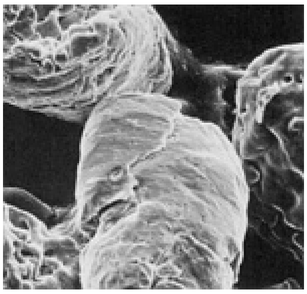


Fig. 3 Scanning electron micrograph of hydrogen-reduced mill scale shown at 750×

Atomization of Liquid Metal

Another major commercial process for production of ferrous powders is atomization of liquid metal by either water or inert gas. Generally, gas atomization is employed for highly alloyed materials (e.g., superalloys and tool steels) and will not be described further here. Both iron-carbon and some prealloyed powders are produced by water atomization. They are used for higher-stress, higher-performance applications.

For the production of iron powder by water atomization of low-carbon iron, molten carbon steel (typically 0.1% C) is poured, either directly or by means of a runner, into a tundish (Fig. 4), which is essentially a reservoir that supplies a uniform and controlled flow of molten metal to the tundish nozzle. The nozzle, which is located at the base of the tundish, controls the shape and size of the metal stream and directs it through an atomizing nozzle system in which the metal stream is disintegrated into fine droplets by the high-velocity atomizing medium. The liquid metal droplets cool and solidify (quench) as they settle to the bottom of the water-filled atomizing tank.

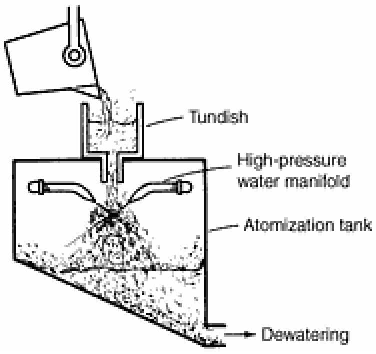


Fig. 4 Schematic of the water atomization process

After magnetic separation, dewatering, and drying, the powder is heated in a belt furnace to about 800 to 1000 °C (1470 to 1830 °F). Furnace atmosphere is hydrogen or dissociated ammonia. During this process, the oxygen content is lowered to less than 0.2%, and the carbon content is reduced to about 0.01%. At the same time, the powder softens through annealing. Subsequent hammer milling of the sinter cake restores the original as-atomized particle size distribution, with only moderate work hardening of the resultant powder. Sieving and blending follow standard practices.

More iron powder (including prealloyed steel powder) is produced by this process than by any other process. The high compressibility and high purity of this powder are the primary reasons for its wide usage. High compressibility, or high pressed-and-sintered density, is desirable in the many applications that require superior mechanical properties. High purity is essential in powder forging and other full-dense processes, where the presence of even small amounts of oxides is detrimental to dynamic properties. Figure 5 shows the irregular shape of a water-atomized steel powder. The particle shape shown is typical of this class of powder.

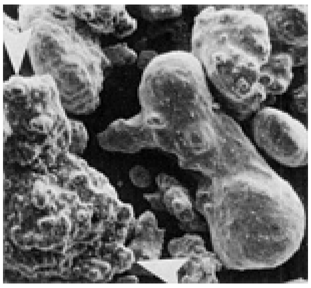


Fig. 5 Scanning electron micrograph of water-atomized iron particles exhibiting a fair degree of irregularity or roughness on the surface (note particle indicated by arrows). 190×

Iron powder may also be produced by water atomizing a high-carbon-content feedstock. In one process, a high-carbon (approximately 3.5% C) steel melt is water atomized to a granular "shot," which is then ball milled to powder size. The ground shot, which contains carbon, is mixed with ground mill scale (iron oxide) that contains oxygen. The carbon and oxygen are chemically combined in a belt furnace at sintering temperatures to form carbon monoxide gas (reducing atmosphere), thus leaving a pure iron cake. The cake is disintegrated to powder size and further refined.

Another process, which utilizes high-carbon pig iron (3.3 to 3.8% C) as the starting feedstock, combines water atomization and partial oxidation of the granulated hot metal. The coarsely granulated iron is then ball milled into powder, which subsequently undergoes a decarburization/annealing step. The reduced-iron cake is further refined by crushing, milling, and blending.

Carbonyl and Electrolytic Iron

Carbonyl iron powders are produced via the thermal decomposition of iron pentacarbonyl, $Fe(CO)_5$. High-purity iron powders produced using carbonyl technology are typically spherical (Fig. 6) and have particle sizes that range from 2 to 20 μm making them suitable for injection-molded parts (conventional powders for cold-die compaction range from 50 to 150 μm). Their high surface area and fine particle size allow the material to sinter to near full density with large associated shrinkages.

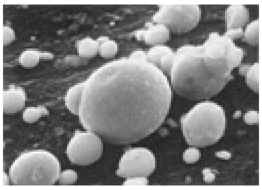


Fig. 6 Scanning electron micrograph of carbonyl iron powder. 3000×

Electrolytic iron powder is produced by electrodeposition of iron from chloride or sulfate baths (electrolytes) onto a stainless steel cathode. A brittle iron deposit is subsequently stripped from the cathode and pulverized in ball mills. The resulting particles are irregularly shaped (flaky) with a fairly rough surface (Fig. 7). The high purity of electrolytic iron makes it suitable for soft magnetic parts, toner carriers in photocopying machines, and enrichment of food products.

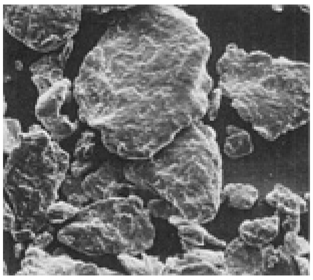


Fig. 7 Scanning electron micrograph of electrolytic iron powder. Note the flaky shape characteristic of these powders. 190×

Compaction and Sintering

Mixing or Blending. Powders are mixed and blended before consolidation. Both lubricant and graphite are added to the ferrous powder. The lubricant--for example, synthetic wax or stearic acid--not only minimizes die friction and wear, but also reduces interparticle friction, allowing the particles to pack more closely and resulting in higher density for the lower range of molding pressures. The amount of lubricant added depends on many factors, including composition of the metal powder, type of tooling, compacted density, and complexity of the part. Amounts generally vary from 0.5 to 1.5 wt%.

The graphite provides carbon for reduction of oxides and the final carbon level of the sintered part. Small percentages of alloying additives, such as nickel or copper, if required to increase strength, are also introduced during final mixing. Powder manufacturers also provide bonded mixes in which $\frac{1}{8}$% of a polymer attaches the additives to the iron powder. This prevents segregation, increases flow rate, and decreases dimensional variation among parts (see the discussion below on "Warm Compaction").

Cold Compaction. Compacting powder serves several important functions: The powder is consolidated into the desired shape--a compact that must be strong enough to withstand subsequent handling; compacting controls the amount and type of porosity of the finished product; and compacting is largely responsible for the final dimensions of the part, subject to dimensional changes during sintering.

Of the numerous compacting methods, closed-die pressure compacting at room temperature is the method that is most commonly used in the production of ferrous P/M parts. Most conventional P/M parts are pressed at pressures ranging from about 415 to 700 MPa (30 to 50 tsi). The pressure exerted depends largely on the required density/strength of the part.

Compaction may also be carried out by cold isostatic pressing. Typically, pressures ranging from 310 to 415 MPa (45 to 60 ksi) are required. Generally, cold isostatic pressing of ferrous P/M parts has rather limited use because of its low production speed. This process is more commonly employed for difficult-to-process materials or for producing highly complex shapes.

Compacting consolidates and densifies the loose powder into a shape called a "green compact." With conventional pressing techniques, the compact has the size and shape of the finished product when ejected from the die. It has sufficient strength (termed green strength) for in-process handling and transport to the sintering furnace.

Warm compaction allows the production of higher-density ferrous P/M parts via a single compaction process. The process utilizes heated tooling and powder during the compaction step. The powder and tooling are typically heated between 130 and 150 °C (260 and 300 °F). In order for the powder premix to perform at these temperatures, a proprietary lubricant system has been developed that provides lower die ejection forces than conventional lubricants. This lubricant system also incorporates a polymeric binder system to limit segregation and provide enhanced flow characteristics of the powder premix. By utilizing warm compaction technology, the green density of the consolidated part can be increased from 0.10 to 0.25 g/cm^3 over traditionally processed (single-pressed/single-sintered) materials. The green strength is typically increased between 50 and 100%. Table 1 compares the green properties of warm-compacted and cold-compacted P/M parts. This increase in green strength provides advantages such as a reduction in green chipping and cracking due to part handling prior to sintering and makes possible the crack-free compaction of complex multiple-level parts. Additionally, the higher green strength provides an opportunity to machine the P/M part in the green state. This capability is critical in the use of high-performance alloy systems that achieve high hardness in the as-sintered state.

Table 1 Effect of processing on the green properties of ferrous compacts

Base material	Processing technique	Compaction pressure		Green density, g/cm^3	Green strength		Peak die ejection force	
		MPa	**tsi**		**MPa**	**psi**	**Mpa**	**tsi**
Ancorsteel 85HP[(a)]	Warm compaction	415	30	7.14	23.2	3370	29.6	2.15
		550	40	7.31	25.4	3685	33.5	2.43
		700	50	7.37	24.7	3580	32.0	2.32
	Cold compaction	415	30	7.00	9.9	1430	37.2	2.70
		550	40	7.19	12.2	1770	50.7	3.68
		700	50	7.29	13.4	1950	53.8	3.90
Distaloy 4800A[(b)]	Warm compaction	415	30	7.07	28.3	4100	27.4	1.99

		550	40	7.29	30.6	4445	31.7	2.30
		700	50	7.36	31.1	4515	32.3	2.37
	Cold compaction	415	30	6.93	12.2	1770	37.2	2.70
		550	40	7.15	15.0	2170	48.5	3.52
		700	50	7.26	16.9	2450	52.0	3.77

Source: Hoeganaes Corporation

(a) Ancorsteel 85HP is a prealloyed steel powder containing 2.0% Ni, 0.85% Mo, 0.4% graphite, and 0.6% lubricant.

(b) Distaloy 4800A is a diffusion-alloyed steel powder containing 4% Ni, 1.5% Cu, 0.50% Mo, 0.5% graphite, and 0.6% lubricant.

As shown in Fig. 1, warm compaction also enables P/M fabricators to single press and single sinter P/M parts to densities as high as approximately 7.4 g/cm^3, which is considerably higher than cold-compacted-and-sintered P/M parts. Traditional methods to increase density and improve mechanical properties, which include double-pressing/double-sintering, copper infiltration, powder forging, or high-temperature sintering, all involve higher costs when compared to single-press/single-sinter warm compaction.

Warm compaction, although applicable to all ferrous material systems, produces the greatest benefits when coupled with high-performance compositions such as diffusion-alloyed steels (described further below) or molybdenum-prealloyed steels. Achieving densities in excess of 7.25 g/cm^3 using these compositions results in mechanical properties that are comparable to steel forgings and ductile iron castings.

Sintering is one of the most complex phenomena in P/M processing. For powder metallurgy, sintering may be generally defined as the process wherein powder particles develop metallurgical bonding and densify under the influence of heat. During sintering of ferrous P/M parts, in particular, the following reactions take place:

- Metallurgical bonds are developed from the mechanical interlocks between powder metal particles in the compact.
- Metal oxides in the powder compact are reduced by reaction with the carbon from the blended graphite powders.
- The desired final carbon level of the P/M compact is obtained by diffusion of carbon from graphite powder.
- Densification of P/M compacts can be achieved during sintering. The degree of densification depends on the sintering parameters and the alloy(s) involved. Generally, higher sintering temperatures and longer sintering times promote greater densification of sintered parts.

The equipment and techniques used in sintering are diversified; there must be a means of heating the parts in a suitable protective atmosphere and a means of controlling the process variables. Heating and cooling rates, time and temperature of sintering, and composition of the atmosphere are the most critical variables. The dimensions of the finished parts are affected by the sintering conditions, as well as by the compacting process and the properties of the powder itself. In the sintering of ferrous metals, the atmosphere serves a dual purpose: it both protects the metal from oxidation and helps to control the carbon content of the parts, especially the carbon content at the surface. Commercial ferrous powders, including prealloyed steel powders, generally contain very little carbon. The carbon content of the finished part is regulated by the amount of graphite mixed into the powder and the carbon potential of the sintering atmosphere. Particularly in alloy steels, the rate of cooling from the sintering temperature can determine which microconstituents are formed as a result of austenite decomposition, but the rate of cooling generally is slow enough to produce ferritic or pearlitic microstructures.

Most ferrous parts are sintered in mesh belt conveyor furnaces at 1105 to 1120 °C (2020 to 2050 °F). Common furnace atmospheres employed include dissociated ammonia (75 vol% H_2, 25 vol% N_2), endothermic gas (40 vol% N_2, 40 vol% H_2, 20 vol% CO with small amounts of water, carbon dioxide, and methane), and nitrogen-base atmospheres (e.g., nitrogen and 10% dissociated ammonia). Vacuum is used for some high-temperature sintering applications. The parts pass through a delubrication zone at 760 to 870 °C (1400 to 1600 °F) and then spend about 15 to 25 min at the high-heat temperature. These furnaces produce 90 to 360 kg/h (200 to 800 lb/h) of parts. They have been improved by the addition of preheat zones that heat rapidly using gas flames to provide an oxidizing environment, which prevents blistering and sooting of parts. Other furnaces have forced atmosphere gas recirculating coolers at the discharge end. These can give finer pearlite spacing or can even form some martensite or bainite, for increased strength.

For higher temperatures and improved toughness, parts are now being sintered in large-scale walking beam furnaces at 1230 to 1315 °C (2250 to 2400 °F). Yield can be up to 900 kg/h (2000 lb/h), with good dimensional control and decreased spread in mechanical properties, as well as increases in the mean properties.

Secondary Operations. In many applications, a P/M part that is made by compacting (either cold or warm) and sintering meets every performance requirement. In other instances, however, the functional requirements (mechanical properties, surface finish/or dimensional tolerances) for a part exceed the capabilities of compacted-and-sintered parts, and one or more secondary operations are required. Some of the common secondary operations are:

- Re-pressing: To increase density as well as strength and ductility; may or may not be accompanied by resintering. Also commonly referred to as double pressing
- Sizing: To tighten dimensional tolerances, usually in the radial direction, relative to the direction of compacting pressure
- Coining: To obtain a definite surface configuration (not to be confused with re-pressing or sizing)
- Machining: To obtain shapes that cannot be compacted, such as by tapping holes or cutting undercut grooves
- Infiltration: To increase strength and decrease porosity
- Heat treating: To increase hardness and strength
- Joining: By sinter bonding, staking, brazing, infiltrating, or welding
- Finishing: Includes deburring, polishing, impregnating, and plating

When the application of a P/M part requires high levels of strength, toughness, or hardness, the mechanical properties can be improved or modified by infiltration, heat treatment, or a secondary mechanical forming operation such as cold (room-temperature) re-pressing. The effect of these secondary processes on P/M mechanical properties is discussed below.

Designation of Ferrous P/M Materials

Powder metallurgy materials are customarily designated by the specifications or standards to which they are made. Comparable standards are published by:

- Metal Powder Industries Federation (MPIF): MPIF Standard 35, Materials Standards for P/M Structural Parts
- ASTM: ASTM B 783, "Standard Specification for Materials for Ferrous Powder Metallurgy Structural Parts"
- International Organization for Standardization (ISO): ISO 5755-2, "Sintered Metal Materials--Specifications Part 2, Sintered Iron and Sintered Steel Containing One or Both of the Elements Carbon and Copper, Used in Structural Parts"; and ISO 5755-3, "Sintered Metal Materials--Specifications Part 3, Sintered Alloyed and Stainless Steels Used for Structural Parts"

Tables 2 and 3 list composition and property requirements, respectively, for ferrous P/M parts/materials per MPIF Standard 35. More detailed information on the material groups described below can be found in this document.

Table 2 Chemical compositions of ferrous P/M structural materials

MPIF designation	Composition range (min to max)[a], wt%				
	Fe	**C**	**Cu**	**Ni**	**Mo**
P/M iron and carbon steel					
F-0000	97.7-100	0-0.3	. . .	. . .	. . .
F-0005	97.4-99.7	0.3-0.6	. . .	. . .	. . .
F-0008	97.1-99.4	0.6-0.9	. . .	. . .	. . .
P/M iron-copper and copper steel					
FC-0200	93.8-98.5	0.0-0.3	1.5-3.9	. . .	. . .
FC-0205	93.5-98.2	0.3-0.6	1.5-3.9	. . .	. . .
FC-0208	93.2-97.9	0.6-0.9	1.5-3.9	. . .	. . .
FC-0505	91.4-95.7	0.3-0.6	4.0-6.0	. . .	. . .
FC-0508	91.1-95.4	0.6-0.9	4.0-6.0	. . .	. . .
FC-0808	88.1-92.4	0.6-0.9	6.0-9.0	. . .	. . .
FC-1000	87.2-90.5	0.0-0.3	9.5-10.5	. . .	. . .
P/M iron-nickel and nickel-steel					
FN-0200	92.2-99.0	0.0-0.3	0.0-2.5	1.0-3.0	. . .
FN-0205	91.9-98.7	0.3-0.6	0.0-2.5	1.0-3.0	. . .
FN-0208	91.6-98.4	0.6-0.9	0.0-2.5	1.0-3.0	. . .
FN-0405	89.9-96.7	0.3-0.6	0.0-2.0	3.0-5.5	. . .

FN-0408	89.6-96.4	0.6-0.9	0.0-2.0	3.0-5.5	. . .
P/M low-alloy steel					
FL-4205	95.90-98.75	0.4-0.7	. . .	0.35-0.55	0.50-0.85
FL-4405	96.35-98.85	0.4-0.7	. . .	. . .	0.75-0.95
FL-4605	94.20-97.50	0.4-0.7	. . .	1.70-2.00	0.40-1.10
FLN-4205	93.95-97.76	0.4-0.7	. . .	1.35-2.50(b)	0.49-0.85
FLN2-4405	93.35-97.95	0.4-0.7	. . .	1.00-3.00	0.65-0.95
FLN4-4405	91.35-95.95	0.4-0.7	. . .	3.00-5.00	0.65-0.95
FLN6-4405	89.35-93.95	0.4-0.7	. . .	5.00-7.00	0.65-0.95
FLNC-4405	90.35-96.95	0.4-0.7	1.0-3.0	1.00-3.00	0.65-0.95
P/M sinter-hardened steel					
FLN2-4408	93.15-97.75	0.6-0.9	. . .	1.00-3.00	0.65-0.95
FLN4-4408	91.15-95.75	0.6-0.9	. . .	3.00-5.00	0.65-0.95
FLN6-4408	89.15-93.75	0.6-0.9	. . .	5.00-7.00	0.65-0.95
FLN-4608	91.00-93.41	0.6-0.9	. . .	3.6-5.0(c)	0.39-1.10
FLC-4608	91.00-96.41	0.6-0.9	1.0-3.0	1.60-2.00	0.39-1.10
FLC-4908	92.40-95.10	0.6-0.9	1.0-3.0	. . .	1.30-1.70
FLNC-4408	90.15-96.75	0.6-0.9	1.0-3.0	1.00-3.00	0.65-0.95
P/M diffusion-alloyed steel					
FD-0205	93.15-96.45	0.3-0.6	1.3-1.7	1.55-1.95	0.4-0.6
FD-0208	92.85-96.15	0.6-0.9	1.3-1.7	1.55-4.95	0.4-0.6

FD-0405	90.70-94.40	0.3-0.6	1.3-1.7	3.60-4.40	0.4-0.6
FD-0408	90.40-94.10	0.6-0.9	1.3-1.7	3.60-4.40	0.4-0.6
P/M copper-infiltrated iron and steel					
FX-1000	82.8-92.0	0.0-0.3	8.0-14.9	. . .	. . .
FX-1005	82.5-91.7	0.3-0.6	8.0-14.9	. . .	. . .
FX-1008	82.2-91.4	0.6-0.9	8.0-14.9	. . .	. . .
FX-2000	72.7-85.0	0.0-0.3	15.0-25.0	. . .	. . .
FX-2005	72.4-84.7	0.3-0.6	15.0-25.0	. . .	. . .
FX-2008	72.1-84.4	0.6-0.9	15.0-25.0	. . .	. . .

Source: MPIF Standard 35, 1997 edition

(a) MPIF standards require that the total amount of all other elements be $\leq$2.0%.

(b) At least 1.0.% Ni is admixed as elemental powder.

(c) At least 2% Ni is admixed as elemental powder.

Table 3 Typical mechanical properties of ferrous P/M materials

Minimum strength values (in ksi) are specified by the two- or three-digit suffix of the material designation code in the first column of the table. Typical values are given in the remaining columns.

Material designation code	Ultimate strength		0.2% offset yield strength		Elongation in 25 mm (1 in.), %	Elastic modulus		Transverse rupture strength		Impact energy[a]		Apparent hardness[b]	Fatigue strength[c]		Density, g/cm^3
	MPa	**ksi**	**MPa**	**ksi**		**GPa**	**10^6 psi**	**MPa**	**ksi**	**J**	**ft · lbf**		**MPa**	**ksi**	
Iron and carbon steel															
F-000-10[d]	120	18	90	13	1.5	105	15.0	250	36	4	3.0	40 HRF	46	7	6.1
F-0000-	170	25	120	18	2.5	120	17.5	340	50	8	6.0	60 HRF	65	10	6.7

15(d)															
F-0000-20(d)	260	38	170	25	7.0	160	23.5	660	95	47	35.0	80 HRF	99	14	7.3
F-0005-15(d)	170	24	120	18	<1.0	105	15.0	330	48	4	3.0	25 HRB	60	9	6.1
F-0005-20(d)	220	32	160	23	1.0	115	16.5	440	64	5	4.0	40 HRB	80	12	6.6
F-0005-25(d)	260	38	190	28	1.5	135	19.5	520	76	7	5.0	55 HRB	100	15	6.9
F-0005-50HT(e)	410	60	(f)	(f)	<0.5	115	16.5	720	105	4	3.0	20 HRC (58 HRC)	160	23	6.6
F-0005-60HT(e)	480	70	(f)	(f)	<0.5	130	18.5	830	120	5	3.5	22 HRC (58 HRC)	190	27	6.8
F-0005-70HT(e)	550	80	(f)	(f)	<0.5	140	20.5	970	140	5	4.0	25 HRC (58 HRC)	220	32	7.0
F-0008-20(d)	200	29	170	25	<0.5	85	12.5	350	51	3	2.5	35 HRB	80	11	5.8
F-0008-25(d)	240	35	210	30	<0.5	110	16.0	420	61	4	3.0	50 HRB	100	14	6.2
F-0008-30(d)	290	42	240	35	<1.0	115	16.5	510	74	5	4.0	60 HRB	120	17	6.6
F-0008-35(d)	390	57	260	40	1.0	140	20.5	690	100	7	5.0	70 HRB	170	25	7.0
F-0008-55HT(e)	450	65	(f)	(f)	<0.5	115	16.5	690	100	4	3.0	22 HRC (60 HRC)	180	26	6.3
F-0008-65HT(e)	520	75	(f)	(f)	<0.5	115	16.5	790	115	5	4.0	28 HRC (60 HRC)	210	30	6.6
F-0008-75HT(e)	590	85	(f)	(f)	<0.5	135	19.5	900	130	6	4.5	32 HRC (60 HRC)	240	34	6.9
F-0008-85HT(e)	660	95	(f)	(f)	<0.5	150	21.5	1000	145	7	5.0	35 HRC (60 HRC)	280	38	7.1

Iron-copper and copper steel															
FC-0200-15[(d)]	170	25	140	20	1.0	95	14.0	310	45	6	4.5	11 HRB	70	10	6.0
FC-0200-18[(d)]	190	28	160	23	1.5	115	16.5	350	51	7	5.0	18 HRB	72	11	6.3
FC-0200-21[(d)]	210	31	180	26	1.5	115	16.5	390	56	7	5.5	26 HRB	80	12	6.6
FC-0200-24[(d)]	230	34	200	29	2.0	135	19.5	430	63	8	6.0	36 HRB	87	13	6.9
FC-0205-30[(d)]	240	35	240	35	<1.0	95	14.0	410	60	<3	<2.0	37 HRB	90	13	6.0
FC-0205-35[(d)]	280	40	280	40	<1.0	115	16.5	520	75	4	3.0	48 HRB	100	15	6.3
FC-0205-40[(d)]	340	50	310	45	<1.0	120	17.5	660	95	7	5.0	60 HRB	140	21	6.7
FC-0205-45[(d)]	410	60	340	50	<1.0	150	21.5	790	115	10	8.0	72 HRB	210	31	7.1
FC-0205-60HT[(e)]	480	70	[(f)]	[(f)]	<0.5	110	16.0	660	95	3	2.5	19 HRC (58 HRC)	190	27	6.2
FC-0205-70HT[(e)]	550	80	[(f)]	[(f)]	<0.5	105	15.5	760	110	5	3.5	25 HRC (58 HRC)	210	30	6.5
FC-0205-80HT[(e)]	620	90	[(f)]	[(f)]	<0.5	130	18.5	830	120	6	4.5	31 HRC (58 HRC)	230	34	6.8
FC-0205-90HT[(e)]	690	100	[(f)]	[(f)]	<0.5	140	20.5	930	135	7	5.5	36 HRC (58 HRC)	260	38	7.0
FC-0208-30[(d)]	240	35	240	35	<1.0	85	12.5	410	60	<3	<2.0	50 HRB	90	13	5.8
FC-0208-40[(d)]	340	50	310	45	<1.0	115	16.5	620	90	3	2.0	61 HRB	120	17	6.3
FC-0208-50[(d)]	410	60	380	55	<1.0	120	17.5	860	125	7	5.0	73 HRB	160	23	6.7

FC-0208-60(d)	520	75	450	65	<1.0	155	22.5	1070	155	9	7.0	84 HRB	230	33	7.2
FC-0208-50HT(e)	450	65	(f)	(f)	<0.5	105	15.0	660	95	3	2.5	20 HRC (60 HRC)	170	25	6.1
FC-0208-65HT(e)	520	75	(f)	(f)	<0.5	120	17.5	760	110	5	3.5	27 HRC (60 HRC)	210	30	6.4
FC-0208-80HT(e)	620	90	(f)	(f)	<0.5	130	18.5	900	130	6	4.5	35 HRC (60 HRC)	240	35	6.8
FC-0208-95HT(e)	720	105	(f)	(f)	<0.5	150	21.5	1030	150	7	5.5	43 HRC (60 HRC)	280	40	7.1
FC-0505-30(d)	300	44	250	36	<0.5	85	12.5	530	77	4	3.0	51 HRB	114	17	5.8
FC-0505-40(d)	400	58	320	47	<0.5	115	16.5	700	102	6	4.5	62 HRB	152	22	6.3
FC-0505-50(d)	490	71	390	56	<1.0	120	17.5	850	124	7	5.0	72 HRB	186	27	6.7
FC-0508-40(d)	400	58	340	50	<0.5	90	13.0	690	100	4	3.0	60 HRB	152	22	5.9
FC-0508-50(d)	470	68	410	60	<0.5	115	16.5	830	120	5	3.5	68 HRB	179	26	6.3
FC-0508-60(d)	570	82	480	70	<1.0	130	18.5	1000	145	6	4.5	80 HRB	217	31	6.8
FC-0808-45(d)	380	55	340	50	<0.5	95	14.0	590	85	4	3.0	65 HRB	144	21	6.0
FC-1000-20(d)	210	30	180	26	<1.0	95	14.0	370	53	5	3.5	15 HRB	80	11	6.0
Iron-nickel and nickel steel															
FN-0200-15(d)	170	25	120	17	3.0	115	16.5	340	50	14	10.0	55 HRF	70	10	6.6
FN-0200-20(d)	240	35	170	25	5.0	140	20.5	550	80	27	20.0	75 HRF	91	13	7.0

FN-0200-25(d)	280	40	210	30	10.0	160	23.5	720	105	68	50.0	80 HRF	103	15	7.3
FN-0205-20(d)	280	40	170	25	1.5	115	16.5	450	65	8	6.0	44 HRB	100	14	6.6
FN-0205-25(d)	340	50	210	30	2.5	135	19.5	690	100	16	12.0	59 HRB	120	18	6.9
FN-0205-30(d)	410	60	240	35	4.0	155	22.5	860	125	28	21.0	69 HRB	150	22	7.2
FN-0205-35(d)	480	70	280	40	5.5	170	24.5	1030	150	46	34.0	78 HRB	180	26	7.4
FN-0205-80HT(e)	620	90	(f)	(f)	<0.5	115	16.5	830	120	5	3.5	23 HRC (55 HRC)	180	26	6.6
FN-0205-105HT(e)	830	120	(f)	(f)	<0.5	135	19.5	1110	160	6	4.5	29 HRC (55 HRC)	240	35	6.9
FN-0205-130HT(e)	1000	145	(f)	(f)	<0.5	150	21.5	1310	190	8	6.0	33 HRC (55 HRC)	290	42	7.1
FN-0205-155HT(e)	1100	160	(f)	(f)	<0.5	155	22.5	1480	215	9	7.0	36 HRC (55 HRC)	320	47	7.2
FN-0205-180HT(e)	1280	185	(f)	(f)	<0.5	170	24.5	1720	250	13	9.5	40 HRC (55 HRC)	370	54	7.4
FN-0208-30(d)	310	45	240	35	1.5	120	17.5	590	85	7	5.5	63 HRB	110	16	6.7
FN-0208-35(d)	380	55	280	40	1.5	135	19.5	720	105	11	8.0	71 HRB	140	20	6.9
FN-0208-40(d)	480	70	310	45	2.0	150	21.5	900	130	15	11.0	77 HRB	170	25	7.1
FN-0208-45(d)	550	80	340	50	2.5	160	23.5	1070	155	22	16.0	83 HRB	190	28	7.3
FN-0208-50(d)	620	90	380	55	3.0	170	24.5	1170	170	28	21.0	88 HRB	220	32	7.4
FN-0208-80HT(e)	620	90	(f)	(f)	<0.5	120	17.5	830	120	5	4.0	26 HRC (57 HRC)	200	29	6.7

FN-0208-105HT(e)	830	120	(f)	(f)	<0.5	135	19.5	1030	150	6	4.5	31 HRC (57 HRC)	260	38	6.9
FN-0208-130HT(c)	1000	145	(f)	(f)	<0.5	140	20.5	1280	185	7	5.5	35 HRC (57 HRC)	320	46	7.0
FN-0208-155HT(e)	1170	170	(f)	(f)	<0.5	155	22.5	1520	220	9	7.0	39 HRC (57 HRC)	370	54	7.2
FN-0208-180HT(e)	1340	195	(f)	(f)	<0.5	170	24.5	1720	250	11	8.0	42 HRC (57 HRC)	430	62	7.4
FN-0405-25(d)	280	40	210	30	<1.0	105	15.5	450	65	6	4.5	49 HRB	100	14	6.5
FN-0405-35(d)	410	60	280	40	3.0	140	20.5	830	120	20	14.5	71 HRB	150	22	7.0
FN-0405-45(d)	620	90	340	50	4.5	170	24.5	1210	175	45	33.5	84 HRB	220	32	7.4
FN-0405-80HT(e)	590	85	(f)	(f)	<0.5	105	15.5	790	115	5	4.0	19 HRC (55 HRC)	180	26	6.5
FN-0405-105HT(e)	760	110	(f)	(f)	<0.5	130	18.5	1000	145	7	5.0	25 HRC (55 HRC)	230	34	6.8
FN-0405-130HT(e)	930	135	(f)	(f)	<0.5	140	20.5	1380	200	9	6.5	31 HRC (55 HRC)	290	42	7.0
FN-0405-155HT(e)	1100	160	(f)	(f)	<0.5	160	23.5	1690	245	13	9.5	37 HRC (55 HRC)	340	49	7.3
FN-0405-180HT(e)	1280	185	(f)	(f)	<0.5	170	24.5	1930	280	18	13.0	40 HRC (55 HRC)	390	57	7.4
FN-0408-35(d)	310	45	280	40	1.0	105	15.5	520	75	5	4.0	67 HRB	110	16	6.5
FN-0408-45(d)	450	65	340	50	1.0	135	19.5	790	115	10	7.5	78 HRB	160	23	6.9
FN-0408-55(d)	550	80	410	60	1.0	155	22.5	1030	150	15	11.0	87 HRB	190	28	7.2
Low-alloy steel															

FL-4205-35[d]	360	52	290	42	1.0	130	18.5	690	100	8	6.0	60 HRB	140	20	6.80
FL-4205-40[d]	400	58	320	47	1.0	140	20.0	790	115	12	9.0	66 HRB	190	27	6.95
FL-4205-45[d]	460	66	360	52	1.5	150	21.5	860	125	16	12.0	70 HRB	220	32	7.10
FL-4205-50[d]	500	73	400	58	2.0	160	23.5	1030	150	23	17.0	75 HRB	280	40	7.30
FL-4205-80HT[e]	620	90	[f]	[f]	<0.5	115	16.5	930	135	7	5.0	28 HRC (60 HRC)	210	30	6.60
FL-4205-100HT[e]	760	110	[f]	[f]	<0.5	130	18.5	1100	160	9	7.0	32 HRC (60 HRC)	260	37	6.80
FL-4205-120HT[e]	900	130	[f]	[f]	<0.5	140	20.5	1280	185	11	8.0	36 HRC (60 HRC)	300	44	7.00
FL-4205-140HT[e]	1030	150	[f]	[f]	<0.5	155	22.5	1480	215	16	12.0	39 HRC (60 HRC)	340	50	7.20
FL-4405-35[d]	360	52	290	42	1.0	120	17.5	690	100	8	6.0	60 HRB	140	20	6.70
FL-4405-40[d]	400	58	320	47	1.0	135	19.5	860	125	15	11.0	67 HRB	190	27	6.90
FL-4405-45[d]	460	66	360	52	1.5	150	21.5	970	140	22	16.0	73 HRB	220	32	7.10
FL-4405-50[d]	500	73	400	58	2.0	160	23.5	1140	165	30	22.0	80 HRB	280	40	7.30
FL-4405-100HT[e]	760	110	[f]	[f]	<1.0	120	17.5	1100	160	7	5.5	24 HRC (60 HRC)	230	34	6.70
FL-4405-125HT[e]	930	135	[f]	[f]	<1.0	135	19.5	1380	200	9	7.0	29 HRC (60 HRC)	290	42	6.90
FL-4405-150HT[e]	1100	160	[f]	[f]	<1.0	150	21.5	1590	230	12	9.0	34 HRC (60 HRC)	330	48	7.10
FL-4405-175HT[e]	1280	185	[f]	[f]	<1.0	160	23.5	1930	280	19	14.0	38 HRC (60 HRC)	400	58	7.30

FL-4605-35(d)	360	52	290	42	1.0	125	18.0	690	100	8	6.0	60 HRB	140	20	6.75
FL-4605-40(d)	400	58	320	47	1.0	140	20.0	830	120	15	11.0	65 HRB	190	27	6.95
FL-4605-45(d)	460	66	360	52	1.5	150	22.0	970	140	22	16.0	71 HRB	220	32	7.15
FL-4605-50(d)	500	73	400	58	2.0	165	24.0	1140	165	30	22.0	77 HRB	280	40	7.35
FL-4605-80HT(e)	590	85	(f)	(f)	<0.5	110	16.0	900	130	6	4.5	24 HRC (60 HRC)	200	29	6.55
FL-4605-100HT(e)	760	110	(f)	(f)	<0.5	125	18.0	1140	165	8	6.0	29 HRC (60 HRC)	260	37	6.75
FL-4605-120HT(e)	900	130	(f)	(f)	<0.5	140	20.0	1340	195	11	8.0	34 HRC (60 HRC)	320	46	6.95
FL-4605-140HT(e)	1070	155	(f)	(f)	<0.5	155	22.5	1590	230	16	12.0	39 HRC (60 HRC)	370	53	7.20
FLN-4205-40(d)	400	58	320	47	1.0	115	16.5	720	105	8	6.0	64 HRB	140	20	6.60
FLN-4205-45(d)	460	66	360	52	1.0	130	18.5	860	125	11	8.0	70 HRB	190	27	6.80
FLN-4205-50(d)	500	73	400	58	1.5	145	21.0	1030	150	18	13.0	77 HRB	220	32	7.05
FLN-4205-55(d)	600	87	430	63	2.0	160	23.5	1210	175	30	22.0	83 HRB	280	40	7.30
FLN-4205-80HF(e)	620	90	(f)	(f)	<1.0	115	16.5	900	130	7	5.0	24 HRC (60 HRC)	190	28	6.60
FLN-4205-105HT(e)	790	115	(f)	(f)	<1.0	130	18.5	1170	170	9	7.0	30 HRC (60 HRC)	250	36	6.80
FLN-4205-140HT(e)	1030	150	(f)	(f)	<1.0	145	21.0	1590	230	12	9.0	36 HRC (60 HRC)	320	47	7.05
FLN-4205-175HT(e)	1280	185	(f)	(f)	1.0	160	23.5	2000	290	19	14.0	42 HRC (60 HRC)	400	58	7.30

Sinter-hardened steel															
FLC-4608-50HT(e)	410	60	(f)	(f)	<1.0	115	16.5	830	120	7	5.0	20 HRC (55 HRC)	. . .	. . .	6.60
FLC-4608-70HT(e)	550	80	(f)	(f)	<1.0	130	18.5	1030	150	9	7.0	26 HRC (55 HRC)	. . .	. . .	6.80
FLC-4608-90HT(e)	690	100	(f)	(f)	<1.0	140	20.5	1310	190	12	9.0	31 HRC (55 HRC)	. . .	. . .	7.00
FLC-4608-110HT(e)	830	120	(f)	(f)	<1.0	155	22.5	1590	230	19	14.0	37 HRC (55 HRC)	. . .	. . .	7.20
Diffusion-alloyed steel															
FD-0205-45(d)	470	68	360	52	1.0	125	18.0	900	130	11	8.0	72 HRB	170	24	6.75
FD-0205-50(d)	540	78	390	57	1.5	140	20.0	1070	155	16	12.0	76 HRB	200	29	6.95
FD-0205-55(d)	610	88	420	61	2.0	150	22.0	1240	180	24	18.0	80 HRB	220	32	7.15
FD-0205-60(d)	690	100	460	67	2.0	170	24.5	1450	210	38	28.0	86 HRB	260	37	7.40
FD-0205-95HT(e)	720	105	(f)	(f)	<1.0	125	18.0	1100	160	7	5.0	28 HRC (55 HRC)	290	42	6.75
FD-0205-120HT(e)	900	130	(f)	(f)	<1.0	140	20.0	1310	190	9	7.0	33 HRC (55 HRC)	360	52	6.95
FD-0205-140HT(e)	1030	150	(f)	(f)	<1.0	150	22.0	1450	210	12	9.0	38 HRC (55 HRC)	450	65	7.15
FD-0205-160HT(e)	1170	170	(f)	(f)	<1.0	170	24.5	1650	240	15	11.0	45 HRC (55 HRC)	520	75	7.40
FD-0208-50(d)	480	69	400	58	<1.0	125	18.0	930	135	9	7.0	80 HRB	170	24	6.75
FD-0208-55(d)	540	79	430	63	<1.0	135	19.5	1070	155	12	9.0	83 HRB	230	33	6.90

FD-0208-60(d)	630	92	470	68	1.0	150	21.5	1240	180	16	12.0	87 HRB	260	38	7.10
FD-0208-65(d)	710	103	500	73	1.0	160	23.0	1340	195	23	17.0	90 HRB	320	46	7.25
FD-0405-55(d)	590	86	430	62	1.0	125	18.0	1100	160	15	11.0	80 HRB	170	25	6.75
FD-0405-60(d)	710	103	460	66	1.0	145	21.0	1340	195	27	20.0	85 HRB	200	28	7.05
FD-0405-65(d)	850	123	480	70	2.5	165	24.0	1590	230	37	27.0	91 HRB	280	40	7.35
FD-0405-100HT(e)	760	110	(f)	(f)	<1.0	125	18.0	1100	160	7	5.0	30 HRC (55 HRC)	230	34	6.75
FD-0405-130HT(e)	970	140	(f)	(f)	<1.0	145	21.0	1380	200	9	7.0	35 HRC (55 HRC)	340	50	7.05
FD-0405-155HT(e)														
FD-0408-50(d)	490	71	390	57	<1.0	120	17.5	900	130	12	9.0	85 HRB	150	22	6.70
FD-0408-55(d)	620	90	430	62	1.0	140	20.0	1140	165	18	13.0	89 HRB	190	27	6.95
FD-0408-60(d)	760	110	460	67	1.5	155	22.5	1380	200	24	18.0	93 HRB	260	38	7.20
FD-0408-65(d)	860	125	490	71	2.0	170	24.5	1590	230	30	22.0	95 HRB	330	48	7.40
Copper-infiltrated steel														
FX-1000-25(d)	350	51	220	32	7.0	160	23.5	910	132	34	25.0	65 HRB	133	19	7.3
FX-1005-40(d)	530	77	340	50	4.0	160	23.5	1090	158	18	13.0	82 HRB	200	29	7.3
FX-1005-110HT(e)	830	120	(f)	(f)	<0.5	160	23.5	1450	210	9	7.0	38 HRC (55 HRC)	230	33	7.3

FX-1008-50[(d)]	600	87	410	60	3.0	160	23.5	1140	166	14	10.0	89 HRB	230	33	7.3
FX-1008-110HT[(e)]	830	120	[(f)]	[(f)]	<0.5	160	23.5	1300	189	9	6.5	43 HRC (58 HRC)	280	41	7.3
FX-2000-25[(d)]	320	46	260	37	3.0	145	21.0	990	144	20	15.0	66 HRB	122	17	7.3
FX-2005-45[(d)]	520	75	410	60	1.5	145	21.0	1020	148	11	8.0	85 HRB	140	20	7.3
FX-2005-90HT[(e)]	690	100	[(f)]	[(f)]	<0.5	145	21.0	1180	171	9	7.0	36 HRC (55 HRC)	160	23	7.3
FX-2008-60[(d)]	550	80	480	70	1.0	145	21.0	1080	156	9	7.0	90 HRB	160	23	7.3
FX-2008-90HT[(e)]	690	100	[(f)]	[(f)]	<0.5	145	21.0	1100	159	7	5.0	36 HRC (58 HRC)	190	27	7.3

Source: MPIF Standard 35, 1997 edition

(a) Unnotched Charpy test.

(b) Apparent hardness measures a combination of matrix hardness plus the effect of porosity. Where applicable, the matrix (converted) hardness is also given in parentheses.

(c) Fatigue limit for 10^7 cycles from reverse-bending tests (R.R. Moore testing machines).

(d) The suffix number represents the minimum yield strength (in ksi) for the material in the as-sintered condition.

(e) The suffix number for the heat treated (HT) or sinter-hardened conditions represents the minimum yield strength (in ksi). Tempering temperature for most heat treated materials is 175 °C (350 °F); nickel steels are tempered at 260 °C (500 °F).

(f) Yield strength and ultimate tensile strength are approximately the same for heat treated materials.

Ferrous Materials Produced from Elemental Powders. The MPIF designations for ferrous P/M materials manufactured from elemental iron powders include a prefix of one or more letters (the first of which is F to indicate an iron-base material), four numerals, and a suffix. The second letter in the prefix, which may be C for copper or N for nickel, identifies the principal alloying element (if one is specified); the percentage of that element is indicated by the first two digits. The third and fourth digits indicate the amount of carbon in the compacted-and-sintered part; the code designation 00 indicates less than 0.3%, 05 indicates 0.3 to 0.6%, and 08 indicates 0.6 to 0.9%. The suffix is used to indicate the minimum 0.2% yield strength of the as-sintered parts and the minimum ultimate tensile strength of heat treated materials in units of 10^3 psi (6.894 MPa). The letters HT indicate heat treated. Ferrous materials produced from elemental powders include the iron and carbon steel, iron-copper and copper steels, and iron-nickel and nickel steels listed in Tables 2 and 3.

Ferrous Materials Produced From Prealloyed Powders. In the case of prealloyed P/M low-alloy steels, the four-digit series described above is replaced with a designation derived from the American Iron and Steel Institute (AISI) coding system. An example would be FL-4605-100HT, where the prefix FL indicates an prealloyed low-alloy ferrous material and the four digits (4605) indicate a nickel-molybdenum low-alloy steel.

When a prealloyed P/M steel powder is modified with elemental additions, a three or four digit alpha-numeric designator is used. For example, FLN-4205 indicates a prealloyed steel powder (FL) with an elemental nickel (N) addition. Compositions and properties of prealloyed low-alloy P/M steels are given in Tables 2 and 3.

Sinter-hardened materials are also produced from prealloyed low-alloy steel powders containing nickel, molybdenum, and manganese as the major alloying elements. They may also contain elemental additions of copper and/or nickel. Due to their compositions, these materials may be quench hardened during the cooling cycle following sintering, thereby eliminating a subsequent heat treating step (i.e., cost savings). Compositions and properties of sinter-hardened P/M steels are given in Tables 2 and 3. They are generally used in applications where high strength and wear resistance are required.

Diffusion-alloyed materials are powders in which the alloying elements of molybdenum, nickel, and copper are added as finely divided elements or oxides to the iron powder. They are then co-reduced with the iron powders at an annealing step, resulting in firm attachment and partial diffusion of the elements to the iron. This partial alloying increases hardenability compared to elemental mixtures, and yet these powders exhibit good compressibility. Diffusion bonding of the alloying elements also reduces the tendency toward powder segregation. Compositions and properties of diffusion-alloyed steels, which are indicated by the prefix FD in MPIF Standard 35, are listed in Tables 2 and 3. As mentioned previously, these materials are also amenable to the warm compaction process. Table 4 compares the properties of diffusion-alloyed steels manufactured by warm compaction and sintering, cold compaction and sintering, and double-pressing/double-sintering (both by cold and warm consolidation methods). These data indicate the superior properties exhibited by the warm compaction process.

Table 4 Effect of processing on the density and transverse rupture strength of sintered ferrous parts

Base material	Processing technique[(a)]	Compaction pressure		Sintered density, g/cm^3	Transverse rupture strength		Hardness, HRB
		MPa	**tsi**		**MPa**	**ksi**	
Ancorsteel 85HP[(b)]	Warm compaction, SP/SS	415	30	7.18	1100	159.5	83
		550	40	7.36	1325	192.1	88
		700	50	7.47	1340	194.6	91
	Warm compaction, DP/DS	415	30	7.36	1340	194.6	89
		550	40	7.54	1495	216.7	92
		700	50	7.63	1530	221.7	94
	Cold compaction, SP/SS	415	30	7.01	995	144.3	79
		550	40	7.22	1145	166.0	85

		700	50	7.32	1280	185.7	88
	Cold compaction, DP/DS	415	30	7.22	1240	180.2	87
		550	40	7.42	1460	212.0	92
		700	50	7.50	1530	221.9	94
Distaloy 4800A[c]	Warm compaction, SP/SS	415	30	7.04	1205	174.8	90
		550	40	7.27	1375	199.6	94
		700	50	7.35	1450	210.1	97
	Warm compaction, DP/DS	415	30	7.20	1505	218.5	94
		550	40	7.40	1690	245.4	97
		700	50	7.49	1695	246.0	100
	Cold compaction, SP/SS	415	30	6.90	975	141.4	81
		550	40	7.08	1265	183.5	87
		700	50	7.20	1340	194.1	91
	Cold compaction, DP/DS	415	30	7.12	1375	199.4	90
		550	40	7.34	1645	238.4	94
		700	50	7.46	1800	261.1	96

Source: Hoeganaes Corporation

(a) SP/SS, single-pressing/single-sintering; DP/DS, double-pressing/double-sintering.

(b) Ancorsteel 85HP is a prealloyed steel powder containing 2.0% Ni, 0.85% Mo, 0.4% graphite, and 0.6% lubricant. Compacts were sintered at 1260 °C (2300 °F).

(c) Distaloy 4800A is a diffusion-alloyed steel powder containing 4.0% Ni, 1.5% Cu, 0.50% Mo, 0.5% graphite, and 0.6% lubricant. Compacts were sintered at 1120 °C (2050 °F).

Copper-Infiltrated Irons and Steels. Infiltration of ferrous P/M compacts with copper (10 to 20% Cu) increases their strength, hardness, fatigue resistance, and impact energy. As shown in Fig. 1, densities on the order of $\leq$7.5 g/cm^3 are readily achieved. This figure also shows one of the disadvantages of copper infiltration--its higher cost. Compositions and properties of infiltrated irons and steels, which are indicated by the prefix FX in MPIF Standard 35, are listed in Tables 2 and 3. Additional information can be found below (see the discussion "Properties of Ferrous P/M Materials").

Properties of Ferrous P/M Materials

The mechanical and physical properties of compacted-and-sintered ferrous P/M materials depend on many factors. Some factors, such as microstructure, chemical composition, and heat treatment, affect the properties of P/M materials just as they affect the properties of wrought or cast steels. However, these factors themselves are affected by conditions unique to the P/M process, such as type of iron powder, whether alloying additions are prealloyed or admixed, type and amount of lubricant added to the powder, variations in the compacting process, and sintering conditions. For example, prealloyed powders generally produce stronger and tougher parts than do powders mixed from elemental metal powders, assuming that the same compacted density is obtained with each powder. The variations in the P/M process, such as compacting pressure and sintering temperature, also affect the properties of P/M materials.

Effect of Porosity/Density. The most obvious distinction between the microstructures of wrought and P/M materials is the porosity often found in P/M materials. This porosity originates as the spaces between powder particles and persists to some extent through sintering and subsequent secondary operations. The microstructure in Fig. 8 shows an example of a pore in a P/M material.

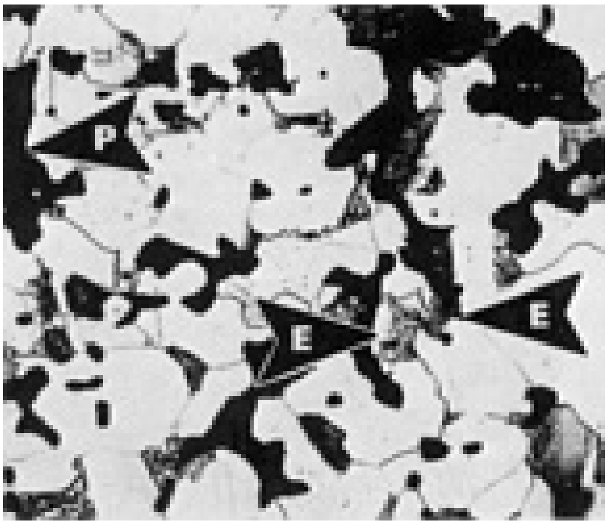


Fig. 8 Atomized iron powder with 0.3% graphite added to yield 0.1 to 0.2% combined carbon (6.7 g/cm^3). Pressed at 410 to 480 MPa (30 to 35 tsi) and sintered 30 min at 1120 °C (2050 °F) in dissociated ammonia. White regions are ferrite. Arrows E surround a colony of eutectoid (pearlite). Arrow P points to a pore. 2% nital. 545×

Powder metallurgy materials are specified in terms of the guaranteed minimum 0.2% tensile yield strength for as-sintered materials, and the minimum ultimate tensile strength for heat treated materials (refer to Table 3). Nonetheless, for a specific base iron powder and degree of sintering, mechanical properties do increase with density. Under the guaranteed minimum property system, the design engineer selects the needed strength properties and chemistry, and the parts fabricator chooses the density, base iron, sintering, and heat treatment to provide the properties. Table 3 shows all the guaranteed minimum tensile properties and related typical properties, including density, for the P/M materials that have been standardized by the MPIF. Table 4 shows the effects of various processing routes on the properties of ferrous P/M parts.

The effects of density on the mechanical properties of heat treated 2% Ni steel, FN-0208, are given in Fig. 9. The effects of density on the mechanical properties of sintered pure iron, F-0000, are shown in Fig. 10.

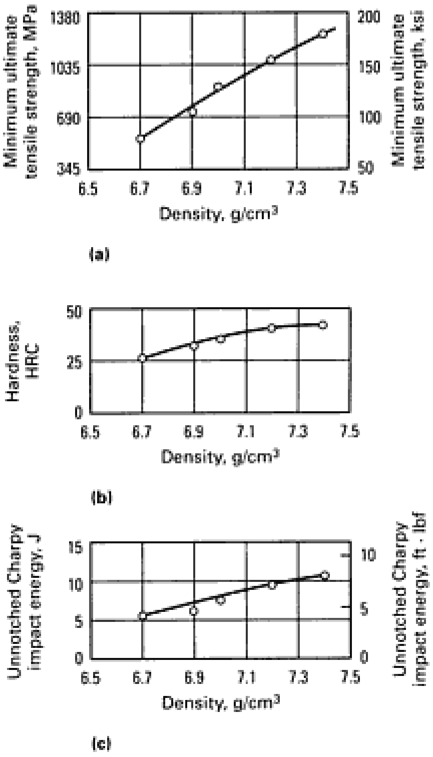


Fig. 9 Effect of density on mechanical properties of heat treated FN-0208 nickel steel. (a) Minimum ultimate tensile strength. (b) Hardness. (c) Impact toughness

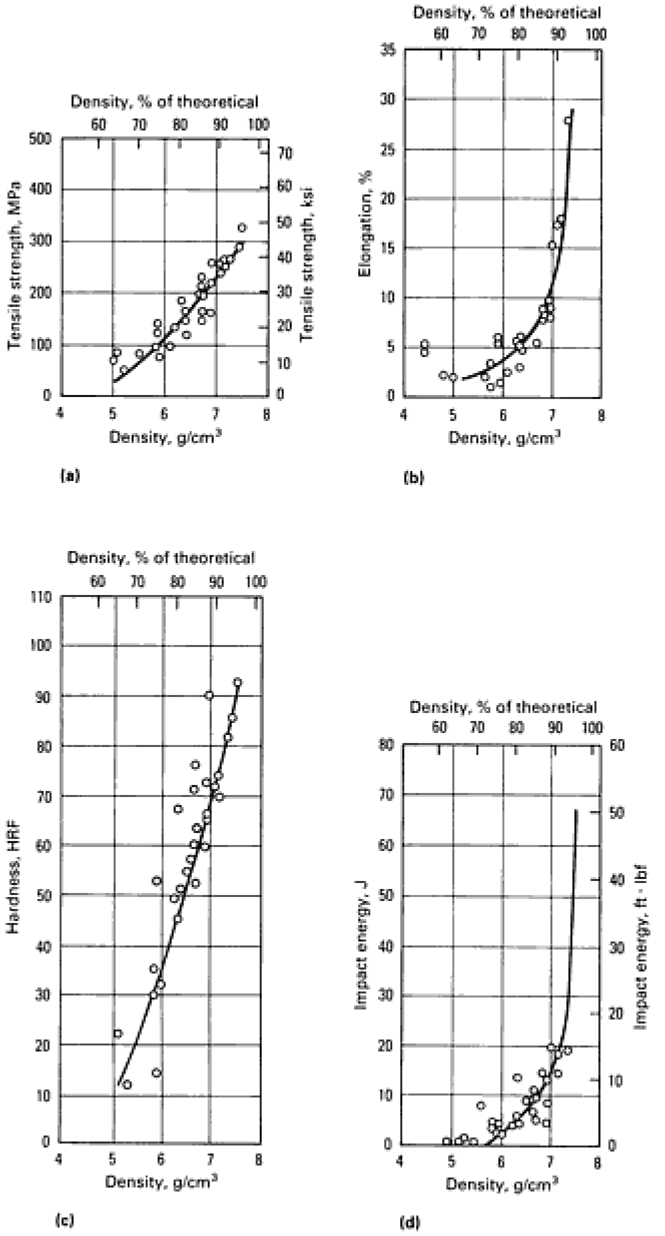


Fig. 10 Effect of density on mechanical properties of sintered iron (F-0000). (a) Tensile strength. (b) Elongation. (c) Hardness. (d) Unnotched Charpy impact energy

The apparent hardness of P/M material is measured with the regular Rockwell hardness tester. The HRC, HRB, and HRF scales measure the resistance to indentation (Table 3). They average the true hardness of the matrix material and the porosity and show lower readings than the corresponding material at full density. They are effective for quality control when applied to a specified region of the part, and an average of five readings is taken. Table 5 shows some typical Rockwell hardnesses and the precision that may be expected.

Table 5 Precision of Rockwell apparent hardness readings on P/M parts

All laboratories tested identical coupons. If similar but different coupons were to be compared, variability would be increased, and larger differences between respective readings would be expected.

MPIF material designation	Density, g/cm^3	Number of laboratories	Average apparent hardness	Repeatability(a) (95% confidence limits)		Reproducibility(a) (95% confidence limits)	
				One reading	**Average of six readings**	**One reading**	**Average of six readings**
F-0000	6.74	9	63.4 HRF	4.0	1.6	4.4	1.8
FC-0208	6.63	9	70.8 HRF	4.5	1.8	5.7	2.3
FX-2008	7.45	9	86.4 HRB	4.3	1.8	4.9	2.0
FL-4605-HT	6.90	8	107.2 HRB(b)	1.9	0.8	3.1	1.3
FL-4605-HT	6.90	8	34.6 HRC	2.2	0.9	3.1	1.3
FC-0208-HT	6.29	10	97.1 HRB(b)	3.1	1.3	4.4	1.8
FC-0208-HT	6.29	10	18.7 HRC	4.2	1.7	5.1	2.1
FN-0208-HT	6.89	10	105.3 HRB(b)	2.9	1.2	4.1	1.7
FN-0208-HT	6.89	10	30.5 HRC	3.8	1.5	4.6	1.9

(a) Repeatability and reproducibility defined according to ASTM E 691.

(b) HRB scale with 1.6 mm ($\frac{1}{16}$ in.) diam carbide ball indenters.

The abrasion or wear resistance of heat treated materials is measured by the 100 g Knoop microhardness. Through the use of a microscope, these hardness measurements, made on the solid regions between the pores, show the intrinsic hardness of the steel matrix. The Knoop microhardness may be directly converted to HRC readings using the method described in MPIF Standard 51, Determination of Microhardness of Powder Metallurgy Materials. The precision or reproducibility between laboratories of the measurement of microhardness on a 4650 heat treated P/M steel is 3 HRC points when the laboratories take the average of six readings and use the conversion method noted above. Comparison of Knoop 100 g readings has a reproducibility between laboratories of 48 points, when the average of six readings are compared between laboratories.

In the range of densities normally encountered, the fatigue strength of a ferrous P/M material is approximately 25 to 40% of its tensile strength, regardless of composition. Typical fatigue strength values are given in Table 3. The effect of porosity on elastic modulus, a property that is generally considered independent of variations in structure, is given in Fig. 11 and in Table 3.

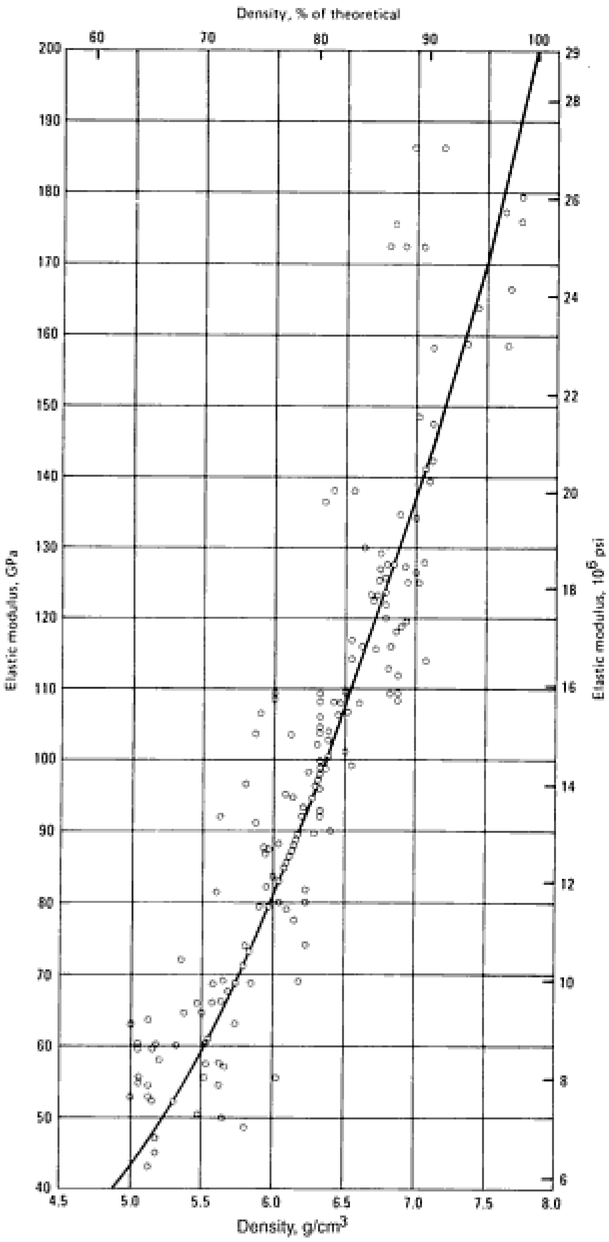


Fig. 11 Effect of density on the elastic modulus of sintered irons and steels after sintering to various densities

Effect of Composition. Alloying elements are added to ferrous P/M materials for the same reasons they are added to wrought or cast steels: primarily to improve strength and hardenability. The alloying elements most commonly used in ferrous P/M materials are carbon, copper, nickel, and molybdenum. The alloying elements are chosen for easy reduction in hydrogen. The amounts of alloying additions are important to the properties of the material, but so are the forms and sources of the alloying elements, particularly, whether they are added as elemental powders or as prealloyed powders. Elemental additions allow better compressibilities, but prealloying gives greater depth of hardening.

Carbon is the most important alloying element in P/M alloys because it strengthens iron and enables it to be heat treated. The effect of carbon content on the ultimate tensile strength of sintered iron is shown in Fig. 12. This strengthening effect can be traced to an increase in the amount of pearlite in the microstructure. As-sintered hypereutectoid P/M steels may have very low strength because proeutectoid cementite forms at austenite grain boundaries. The brittle cementite between the pores can fracture under relatively low levels of macroscopic stress. Combined carbon contents exceeding 0.8% are not recommended.

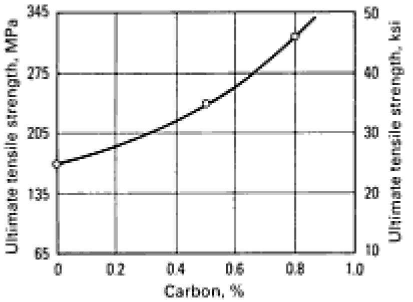


Fig. 12 Tensile properties of as-sintered iron-carbon alloys at 6.7 g/cm^3 as a function of carbon content

Iron and prealloyed steel powders are usually made with very low carbon content to maximize their compressibilities; carbon is added to these powders as admixed graphite. The carbon content of the sintered compact is also affected by the composition of the sintering atmosphere. The amount of graphite that is retained in the sintered compact as combined carbon depends on the sintering atmosphere and temperature, the source and type of both the graphite and the metal powder, and the amount and types of oxides in the metal powder. The correct graphite addition is determined empirically for each lot of iron powder.

Copper increases the strength of ferrous P/M materials, as shown in Fig. 13, primarily through solid-solution strengthening. Copper is also thought to accelerate the sintering and homogenizing processes, particularly if elemental copper or a copper-rich master alloy exists in the liquid state during the early stages of sintering. Copper causes atomized iron-base compacts to expand during sintering; thus, additions of copper can be used to compensate for shrinkage in iron-carbon or Fe-C-Ni alloys. Sponge iron blends with elemental copper do not expand.

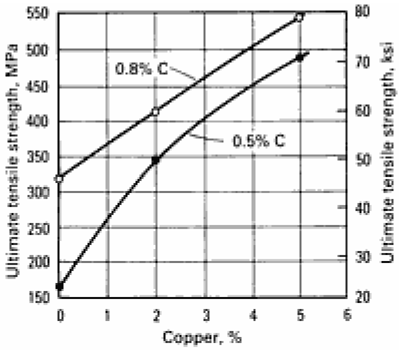


Fig. 13 Effect of copper and carbon content on the tensile strength of ferrous P/M materials

Nickel strengthens ferrous P/M alloys by solid-solution strengthening and increases their hardenability. The effect of nickel content on the mechanical properties of P/M nickel steels is given in Fig. 14. The presence of nickel increases shrinkage during sintering; additions of copper help maintain dimensions during sintering. The heterogeneous microstructure with nickel-rich islands (see Fig. 15) decreases notch sensitivity and raises tensile strength and impact resistance of the heat treated materials. The copper helps dissolve nickel in iron and increases hardenability.

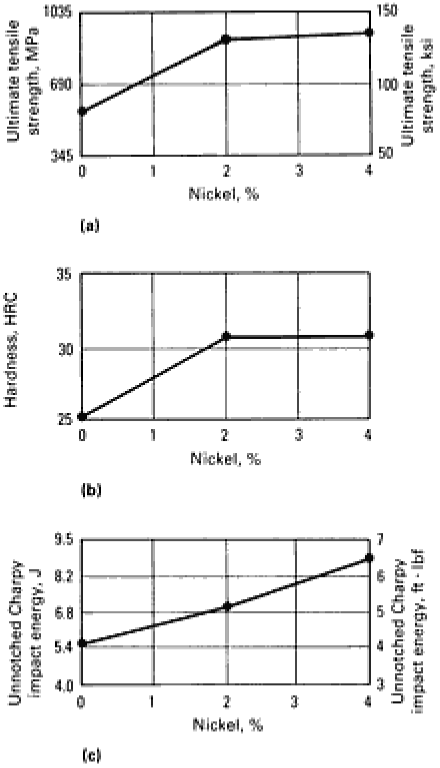


Fig. 14 Effect of nickel on the mechanical properties of heat treated P/M steels (7.0 g/cm$_3$). (a) Ultimate tensile strength. (b) Hardness. (c) Impact toughness

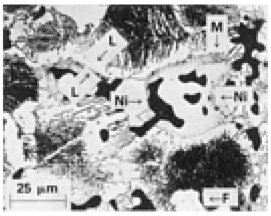


Fig. 15 Microstructure of sintered Fe-2Ni-0.5C alloy. Sintered for 30 min at 1120 °C (2050 °F). Arrows marked Ni outline nickel-rich particle. Arrow M, martensite or bainite at nickel-rich boundary. Arrows marked L, diffusion layer between nickel and pearlite. This is not unalloyed ferrite. Arrow F, ferrite. 4% nital etched

Molybdenum and nickel are the elements most frequently added to iron powders to improve hardenability. The amounts of these elements are relatively small, as in the MPIF designations FL-4605 and FL-4205. These two commonly used prealloyed powders correspond in composition to 46xx and 42xx wrought steels except that they have a higher molybdenum content and a lower manganese content.

Some prealloyed steels (sinter-hardening steels) with extra molybdenum and manganese, when blended with 2% Cu and eutectoid carbon, have enough hardenability to air harden during normal belt furnace sintering. After sintering, parts are tempered 1 h at 175 °C (350 °F).

Phosphorus can reduce the temperature used for sintering. It forms a liquid phase, giving rapid pore rounding, strengthening, and toughening when used in amounts of 0.45 to 0.80% P. It also reduces the hysteresis losses in magnetic core applications. The hot shortness that phosphorus causes in wrought steels is generally not a problem in P/M materials.

Sulfur may be added to ferrous P/M materials to improve machinability. The amounts of sulfur used in P/M materials exceed those used in wrought steels; however, sulfur contents as high as 1.0% appear to have little effect on the mechanical properties of as-sintered compacts. Sulfur may be prealloyed to form MnS in situ, added as elemental sulfur to sponge iron, or added as manganese sulfide powder. The prealloyed form can decrease drill times by a factor of two.

Alloying elements having oxides that are stable in typical sintering atmospheres are used sparingly, if at all, in low-alloy ferrous P/M materials. Manganese and chromium are sometimes used in very small amounts; vanadium and titanium are rarely used.

Effect of Infiltration. The infiltration of ferrous P/M materials is a common processing technique. Infiltrants, usually copper-base alloys, are placed in contact with the green compact, and the two are sintered together at a temperature above the melting point of the infiltrant. Capillary action draws the infiltrant into the ferrous compact, where it can promote the sintering of iron particles. In an alternative technique, the ferrous compact is sintered and then infiltrated in a second step.

As indicated in Fig. 16 and Table 3, infiltration increases the strength, hardness, fatigue strength, and impact energy of ferrous P/M products compared to the iron-carbon matrix. Infiltration increases the density of the part (Fig. 1) and decreases variations in density. Porosity can be partly or completely eliminated by infiltration. As the infiltrant runs in under capillary action, it fills the higher-density fine-pore regions first. Recent proprietary techniques have increased unnotched impact toughness to more than 200 J (150 ft · lbf). Some of the disadvantages of infiltration are its high cost (Fig. 1), the likelihood of growth of the part during infiltration, and the possibility of erosion of the surface of the compact by the infiltrant.

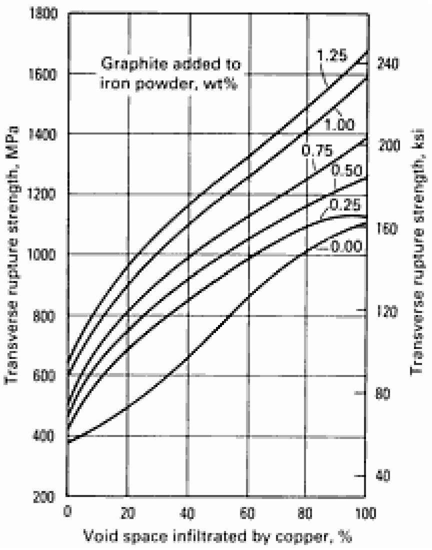


Fig. 16 Effect of infiltration on transverse rupture strength of iron-carbon alloys sintered to a density of 6.4 g/cm^3. Combined carbon in the alloys was about 80% of the amount of graphite added to the iron powder. The amount of copper infiltrant was adjusted to fill various fractions of void space.

Effect of Heat Treatment. Ferrous P/M materials may be heat treated in the same manner as wrought or cast steels of comparable compositions. The porosity in P/M materials can cause complications, such as apparent loss of hardenability, greater depth of carburization or decarburization, and possible entrapment of quenchants. The effect of porosity on hardenability, which is exaggerated in measurements of apparent hardness, is shown in Fig. 17. The reduction in hardenability was caused by the reduced thermal conductivity of the porous sintered compact. The effect of porosity on depth of carbon is shown in Fig. 18. The porosity of the sintered compact enables the carbonitriding gas to penetrate well below the surface, hardening the compact to a greater depth. The use of vacuum carburizing for 2 to 10 min, followed by quenching, can form a definite case on low-carbon parts with a density as low as 6.8 g/cm^3.

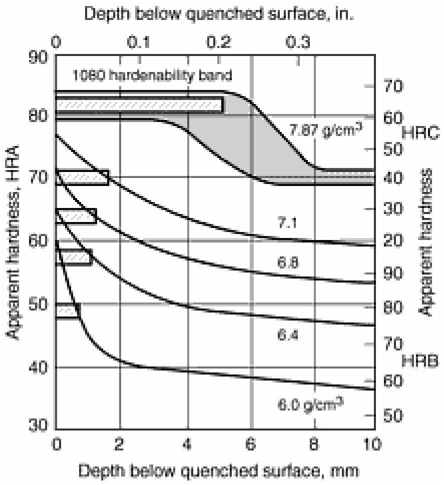


Fig. 17 Effect of porosity on hardenability. Compacts of F-0008 powder were pressed and sintered to various densities, then austenitized and end quenched. Apparent hardness traverses reflect both depth of hardening and density of compacts. Horizontal bars represent approximate distance over which the average amount of martensite in the microstructure exceeded 50%. Hardenability band for 1080 wrought steel, which has a higher manganese content, is included for comparison.

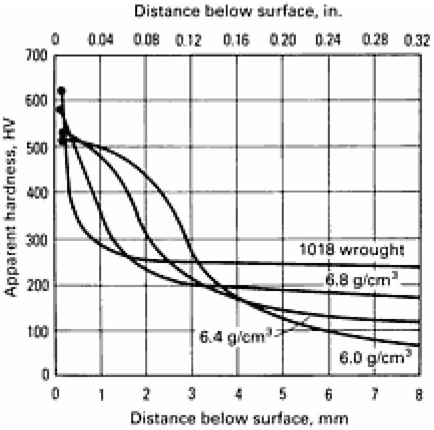


Fig. 18 Effect of porosity on carbonitriding. Compacts of F-0000 powder were pressed and sintered to various densities, then carbonitrided. Hardness traverses reflect both depth of carbonitrided case and density of compacts. Hardness traverse for a carbonitrided specimen of wrought 1018 steel is included for comparison.

The effect of various tempering temperatures on the properties of FN-0205 nickel steel is shown in Fig. 19. Tensile strength data for a wrought steel of comparable composition is also given in this figure to illustrate the deleterious effect of porosity on the strength of P/M materials.

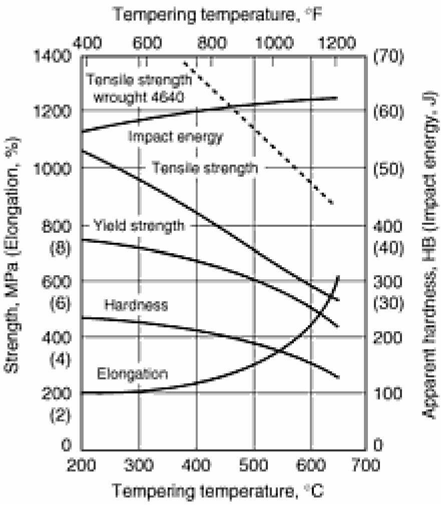


Fig. 19 Effect of tempering temperature on the mechanical properties of hardened-and-tempered FN-0205 sintered nickel steel. Specimens were hardened by quenching from 870 °C (1600 °F) and tempering at various temperatures. Tensile data for wrought 4640 steel is included for comparison.

Steam treating is a heat treatment sometimes applied to ferrous P/M materials. A typical treatment might be 2 h in superheated steam at 540 to 600 °C (1000 to 1100 °F). In such a treatment, a layer of black iron oxide (Fe_3O_4) is formed on the surfaces of the sintered part, including the surfaces of pores that are connected to the surface. The process increases the density, hardness, compressive strength, and resistance to wear and corrosion of the part. The effect of steam treating on the density and hardness of several ferrous P/M materials is given in Table 6. Steam treating can reduce the tensile strength, elongation, and impact strength below the as-sintered values (Table 7). The ductility of steam-treated P/M steels is significantly reduced because of the internal stresses created by the formation of the iron oxide. Care must be taken when treating high-carbon P/M steels because these internal stresses can initiate microcracking and cause severe loss of ductility. Many cases have been reported in which parts were accidentally dropped on the floor after being steam treated, and the parts subsequently shattered like glass. The best recommendation for preventing such an incident is to specify a 0.5% C (max) content on materials that are to be steam treated.

Table 6 Effect of steam treating on the density and hardness of ferrous P/M materials

Material	Density, g/cm^3		Apparent hardness	
	Sintered	**Steam treated**	**Sintered**	**Steam treated**
F-0000	5.8	6.2	7 HRF	75 HRB
F-0000	6.2	6.4	32 HRF	61 HRB
F-0000	6.5	6.6	45 HRF	51 HRB
F-0008	5.8	6.1	44 HRB	100 HRB
F-0008	6.2	6.4	58 HRB	98 HRB
F-0008	6.5	6.6	60 HRB	97 HRB

FC-0700	5.7	6.0	14 HRB	73 HRB
FC-0700	6.3	6.5	49 HRB	78 HRB
FC-0700	6.6	6.6	58 HRB	77 HRB
FC-0708	5.7	6.0	52 HRB	97 HRB
FC-0708	6.3	6.4	72 HRB	94 HRB

Table 7 Comparison of average mechanical properties of steam-blackened P/M materials with as-sintered properties and typical values from MPIF Standard 35 (see Table 3)

Material	Blackening(a)	Ultimate tensile strength		Average-density ultimate tensile strength		Elongation in 25 mm (1 in.), %	Transverse rupture strength		Impact energy(b)		0.2% offset yield strength		Hardness, HRB
		MPa	**ksi**	**MPa**	**ksi**		**MPa**	**ksi**	**J**	**ft · lbf**	**MPa**	**ksi**	
F-0000	None	138	20.0	42.7	6.20	6.4	330	47.9	5.4	4.0	. . .	. . .	37
	Light	154	22.3	45.0	6.52	1.8	367	53.2	2.7	2.0	. . .	. . .	88
	Heavy	152	22.1	44.6	6.47	1.2	434	63.0	2.7	2.0	. . .	. . .	85
Standard 35	None	124	18.0	. . .	. . .	1.5	248	36.0	4.1	3.0	690	10	40 HRF
F-0008	None	211	30.6	43.2	6.26	1.5	453	65.7	3.6	2.7	. . .	. . .	69
	Light	134	19.4	45.6	6.61	0.4	434	63.0	2.3	1.7	. . .	. . .	108
	Heavy	116	16.8	45.4	6.59	0.4	450	65.2	2.4	1.8	. . .	. . .	106
Standard 35	None	241	35.0	. . .	. . .	<0.5	420	61	4.1	3	170	25	50
F-0208	None	331	48.0	43.2	6.27	1.2	684	99.2	4.7	3.5	. . .	. . .	87
	Light	208	30.2	45.1	6.54	0.4	606	87.9	2.7	2.0	. . .	. . .	112
	Heavy	205	29.8	44.9	6.51	0.7	738	107	2.7	2.0	. . .	. . .	110

Standard 35	None	345	50	. . .	. . .	<1.0	620	90	2.7	2.0	275	40	61

(a) None, as sintered; light blackening, 2 h exposure in 538 °C (1000 °F) steam; heavy blackening, 4 h exposure in 538 °C (1000 °F) steam. Unnotched Charpy test at room temperature

Effect of Re-Pressing. As a secondary mechanical forming operation performed at room temperature, re-pressing (or double pressing) is done primarily to increase density, which increases mechanical and physical properties and hardness. When re-pressing is performed primarily to increase dimensional accuracy rather than density, it is termed sizing. When re-pressing is intended to change the contour of the surface in contact with the punches, it is termed coining. For example, a sintered blank could be coined so that the surface is indented with small slots or letters and numbers.

The amount of material deformation achieved with re-pressing is greater than in sizing because the forces used are greater than the sizing forces. The reduction in height of a ferrous part generally ranges from 3 to 5%. As with sizing, part tolerance after re-pressing depends on material type and part size.

Re-pressing generally refers to the application of high pressures on a sintered part at room temperature, while powder forging refers to processes in which a P/M preformed part is kept at an elevated temperature during the application of high pressure. At room temperature and at pressures as high as or higher than the compacting pressure, re-pressing increases the strength of a sintered P/M part by decreasing its porosity and by cold working the metal. The part is considerably strengthened, but at the expense of ductility. Resintering after re-pressing increases the ductility and toughness of the part without diminishing its strength. Table 4 lists the property benefits obtained by using re-pressing and resintering. As shown in Fig. 1, however, the disadvantage of re-pressed and resintered parts lies in their relatively high cost. Those materials that are difficult to re-press after sintering usually can be re-pressed if the sintering is done at a low temperature at which alloying cannot take place; this low-temperature sintering is called presintering. For iron alloys, presintering is done at 845 °C (1550 °F).

The effect of re-pressing on the density of ferrous P/M materials is shown in Fig. 20. The density that is achieved by re-pressing depends on the density of the sintered or presintered compact, the re-pressing pressure and lubricant, and whether the powder used was prealloyed or mixed from elemental powders.

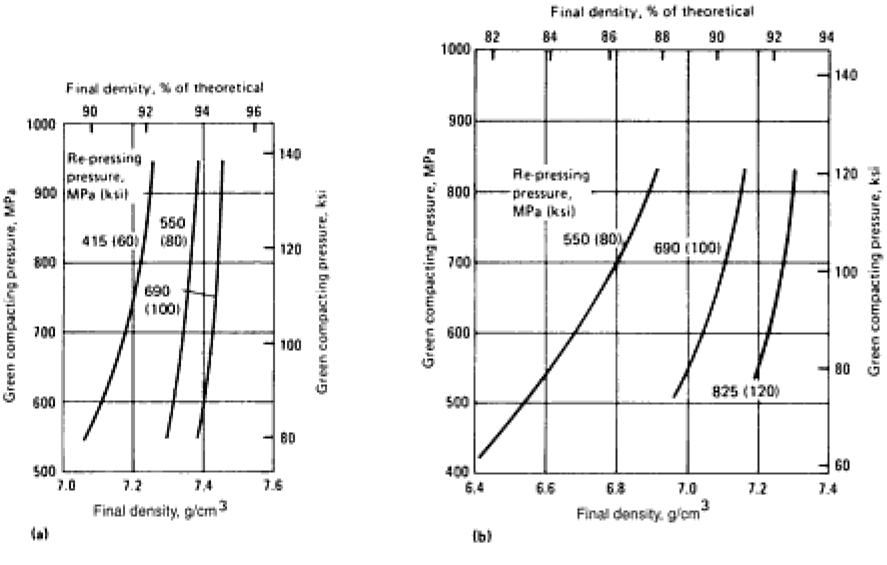


Fig. 20 The effect of re-pressing on density of P/M compacts. Alloy steel powders (4640 composition) were compacted at various pressures, then sintered, re-pressed, and resintered. For each specimen, the final density is indicated by the intersection between the curve that indicates the re-pressing pressure and the grid line that indicates the green compacting pressure. (a) Prealloyed powder. (b) Diffusion-alloyed powder

High-Density Ferrous Powder Metallurgy Parts

Introduction

FERROUS PARTS of near and full theoretical density can be produced by a variety of thermomechanical methods. These methods involve various amounts of heat and mechanical work to aid densification of the powder mass. For production of low-alloy steel parts, powder forging and injection molding have received the most attention. Both of these powder process technologies are formulated specifically to yield a product as close to full density as possible. This contrasts significantly with the conventionally processed products where attainment of full density is not the primary goal.

Powder Forging

Powder forging involves fabrication of a preform by conventional press-and-sinter processing, followed by hot forging of the preform, which is quite porous, into a final shape with substantial densification. Forging is generally performed in one blow in confined dies to eliminate flash formation and achieve net shapes. Thus, parts containing through holes and complex configurations can be manufactured with little or no material loss due to trimming, hole punching, machining, or grinding. Powder forging is used to obtain higher density in P/M parts for high-stress applications, where pores must be minimized or completely eliminated.

There are two basic forms of powder forging:

- Hot upsetting, in which the preform experiences a significant amount of lateral material flow
- Hot re-pressing, in which material flow during densification is mainly in the direction of pressing; sometimes referred to as hot restriking, or hot coining

These two deformation modes and the stress conditions they impose on pores are illustrated in Fig. 1.

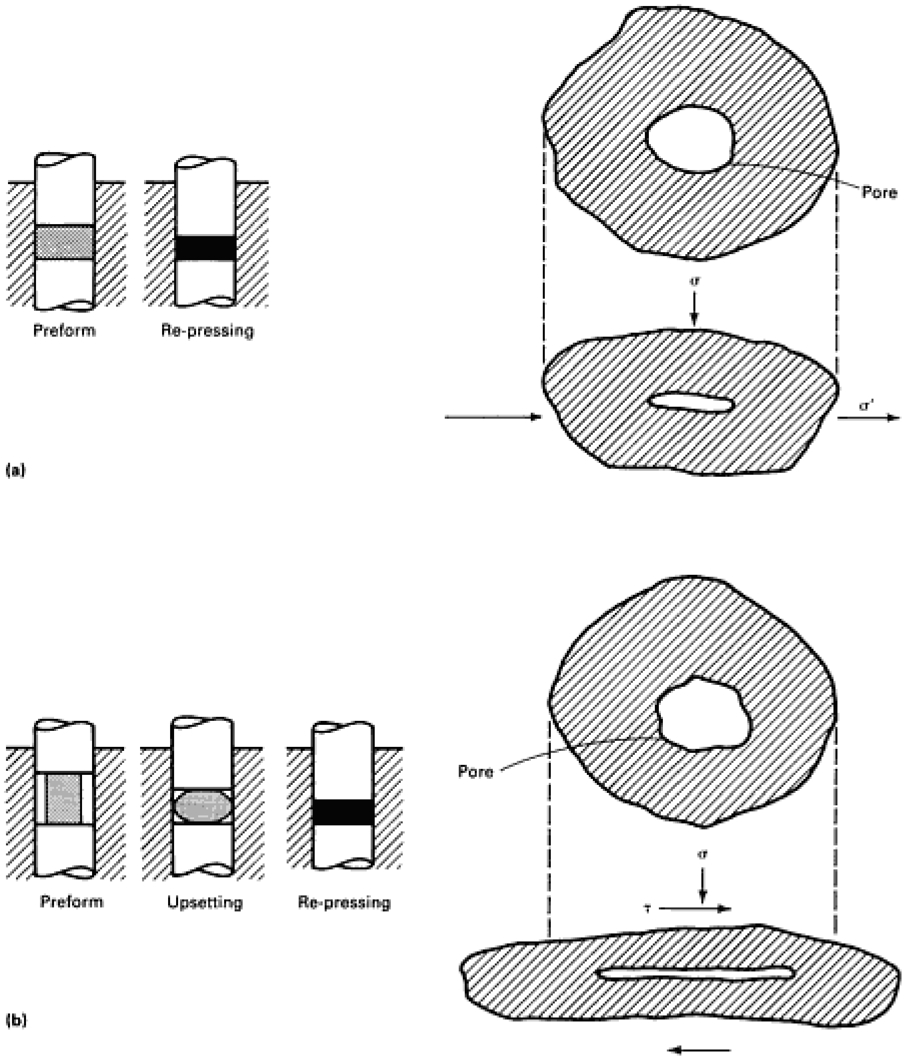


Fig. 1 Forging modes and stress conditions on pores for (a) re-pressing and (b) upsetting

In hot upset powder forging, the extensive unconstrained lateral flow of material results in a stress state around the pores that is a combination of normal and shear stresses. A spherical pore becomes flattened and elongated in the direction of lateral flow. The sliding motion due to shear stresses breaks up any residual interparticle oxide films and leads to strong metallurgical bonding across collapsed pore interfaces. This enhances dynamic properties such as fracture toughness and fatigue strength.

The stress state during hot re-press powder forging consists of a small difference between vertical and horizontal stresses, which results in very little material movement in the horizontal direction and thus limited lateral flow. As densification proceeds, the stress state approaches a pure hydrostatic condition. A typical pore simply flattens, and the opposite sides of the pore are brought together under pressure. Hot re-press forging requires higher forging pressures than does hot upset forging for comparable densification. The decreased interparticle movement compared with upsetting reduces the tendency to break up any residual interparticle oxide films and may result in lower ductility and toughness.

While powder forged parts are primarily used in automotive applications where they compete with cast and wrought products, parts have also been developed for military and off-road equipment. Typical automotive applications include connecting rods and components for automatic transmissions.

Material Considerations

The initial production steps of powder forging (preforming and sintering) are identical to those of the conventional press and sinter P/M process. Certain defined physical characteristics and properties are required in the powders used in these processes. In P/M parts, surface finish is related to the particle size distribution of the powder. In powder forging, however, the surface finish is directly related to the finish of the forging tools.

Typical pressing grades are -80 mesh with a median particle size of about 75 μm. The apparent density and flow are important for maintaining fast and accurate die filling. The chemistry affects the final alloy produced, as well as the compressibility.

Green strength and compressibility are more critical in conventionally processed P/M parts than they are in powder forging applications. Although there is a need to maintain edge integrity in powder forging preforms, there are rarely thin, delicate sections that require high green strength. Because powder forging preforms do not require high densities (typically 6.2 to 6.8 g/cm^3), the compressibility obtainable with prealloyed powders is sufficient. However, carbon is not prealloyed because it has an extremely detrimental effect on compressibility.

The two principal requirements for powder forged materials are a capability to develop an appropriate hardenability that will guarantee strength and to maximize fatigue performance by the control of microstructural features such as inclusions.

Hardenability. Nickel and molybdenum have the advantage that their oxides are reduced at conventional sintering temperatures. Alloy design is therefore a compromise, and the majority of atomized prealloyed powders in commercial use are nickel/molybdenum-base, with manganese present in limited quantities. The compositions of three commercial P/M steels are:

Alloy	Composition(a), wt%		
	Mn	**Ni**	**Mo**
P/F-4600	0.10-0.25	1.75-1.90	0.50-0.60
P/F-4200	0.25-0.35	0.40-0.50	0.35-0.65

(a) All compositions contain balance of iron.

The higher cost of nickel and molybdenum, along with the higher cost of powder, compared with conventional wrought materials, is often offset by the higher material utilization inherent in the powder forging process.

More recently, powder forged parts have been produced from iron powders (0.10 to 0.25% Mn) with copper and/or graphite additions for parts that do not require the heat treating response or high-strength properties achieved through the use of the low-alloy steels.

Inclusion Assessment. Because the properties of material powder forged to near full density are strongly influenced by the composition, size distribution, and location of nonmetallic incisions, a method has been developed for assessing the inclusion content of powders intended for powder forging applications. Samples of powders intended for forging applications are re-press powder forged under closely controlled laboratory conditions. The resulting compacts are sectioned and prepared for metallographic examination. The inclusion assessment technique involves the use of automatic image analysis equipment. The compact used for inclusion assessment may also be used to measure the amount of unalloyed iron powder particles present.

Process Considerations

The development of a viable powder forging system requires the consideration of many process parameters. The mechanical, metallurgical, and economic outcomes depend to a large extent on operating conditions, such as temperature, pressure, flow/feed rates, atmospheres, and lubrication systems. Equally important consideration must be given to the types of processing equipment, such as presses, furnaces, dies, and robotics, and to secondary operations, in order to obtain the process conditions that are most efficient. This efficiency is maintained by optimizing the process line layout.

Preforming. Preforms are manufactured from admixtures of metal powders, lubricants, and graphite. Compaction is predominantly accomplished in conventional P/M presses that use closed dies.

The control of weight distribution within preforms is essential to produce full density and thus maximize performance in the critical regions of the forged component. Excessive weight in any region of the preform may cause overload stresses that could lead to tool breakage at forging.

Successful preform designs have been developed by an iterative trial-and-error procedure, using prior experience to determine the initial shape. More recently, computer-aided design (CAD) has been used for preform design.

Preform design is intimately related to the design and dimensions of the forging tooling, the type of forging press, and the forging process parameters. Among the variables to be considered for the preforming tools are:

- Temperature, that is, preform temperature, die temperature, and, when applicable, core rod temperature
- Ejection temperature of the forged part
- Lubrication conditions, that is, influence on compaction/ejection forces and tooling temperatures
- Transfer time and handling of the preform from the preheat furnace to the forging die cavity

Correct preform design not only entails having the right amount of material in the various regions of the preform, but also is concerned with material flow between the regions and prevention of potential fractures and defects.

Sintering and Reheating. Preforms may be forged directly from the sintering furnace; sintered, reheated, and forged; or sintered after the forging process. The basic requirements for sintering in a ferrous powder forging system are:

- Lubricant removal
- Oxide reduction
- Carbon diffusion
- Development of particle contacts
- Heat for hot densification

Oxide reduction and carbon diffusion are the most important aspects of the sintering operations. For most ferrous powder forging alloys, sintering takes place at about 1120 °C (2050 °F) in a protective reducing atmosphere with a carbon potential to prevent decarburization. Typical P/M sintering has been performed at 1120 °C (2050 °F) for 20 to 30 min. Increases in temperature reduce the time required for sintering by improving oxide reduction and increasing carbon diffusion. Chromium-manganese steels have been limited in their use because of the higher temperatures required to reduce their oxides and the greater care needed to prevent reoxidation.

Any of the furnaces used for sintering P/M parts, such as vacuum, pusher, belt, rotary hearth, walking beam, roller hearth, and batch/box, may be used for sintering or reheating powder forged preforms. The sintered preforms may be forged directly from the sintering furnace; stabilized at lower temperatures and forged; or cooled to room temperature, reheated, and forged. All cooling, temperature stabilization, and reheating must occur under protective atmosphere to prevent oxidation.

Induction furnaces are often used to reheat axisymmetric preforms to the forging temperature because of the short time required to heat the material. Difficulties may be encountered in obtaining uniform heating throughout asymmetric shapes because of the variation in section thickness.

The Forging Process. Powder forging involves removing heated preforms from a furnace, usually by robotic manipulators, and locating them in the die cavity for forging at high pressures (690 to 965 MPa, or 100 to 140 ksi). Preforms may be graphite coated to prevent oxidation during reheating and transfer to the forging die. Lubrication of the die and punches is usually accomplished by spraying a water-graphite suspension into the cavity.

The forging presses commonly used in conventional forging, including hammers, high-energy-rate forming machines, mechanical presses, hydraulic presses, and screw presses, have been evaluated for use in powder forging. The essential characteristics that differentiate presses are contact time, stroke velocity, available energy and load, stiffness, and guide accuracy.

Metal Flow in Powder Forging. Draft angles, which facilitate forging and ejection in conventional forging, are eliminated in powder forged parts. This means that greater ejection forces--on the order of 15 to 20% of press capacity as a minimum--are required for the powder forging of simple shapes. However, the elimination of draft angles permits P/M parts to be forged closer to net shape.

Tool Design. In order to produce sound forged components, the forging tooling must be designed to take into account:

- Preform temperature
- Die temperature
- Forging pressure
- The elastic strain of the die
- The elastic/plastic strain of the forging
- The temperature of the part upon ejection
- The elastic strain of the forging upon ejection
- The contraction of the forging during cooling
- Tool wear

Specified part dimensional tolerances can only be met when the above parameters have been taken into account. However, there is still some flexibility in the control of forged part dimensions even after die dimensions have been selected. Higher preform ejection temperatures result in greater shrinkage during cooling. Increases in die temperature expand the die cavity and thus increase the size of the forged part. Therefore, if the forgings are undersize for a given set of forging conditions, a lower preform preheat temperature and/or a higher die preheat temperature can be used to produce larger parts. On the other hand, if the forged parts are oversize, the preform preheat temperature could be raised and/or the die temperature lowered to bring the parts to the desired size.

Secondary Operations. In general, the secondary operations applied to conventional components such as plating and peening may be applied to powder forged components. The most commonly used secondary operations involve deburring, heat treating, and machining.

The powder forged components may require deburring or machining to remove limited amounts of flash formed between the punches and the die. This operation is considerably less extensive than that required for wrought forgings.

The heat treatment of P/M products is the same as that required for conventionally processed materials of similar composition. The most common heat treating practices involve treatments such as carburizing, quench-and-temper cycles, or continuous-cooling transformations.

The amount of machining required for powder forged components is generally less than the amount required for conventional forgings because of their improved dimensional tolerances. Standard machining operations may be used to achieve final dimensions and surface finish. One of the main economic benefits of powder forging is the reduced amount of machining required, as illustrated in Fig. 2.

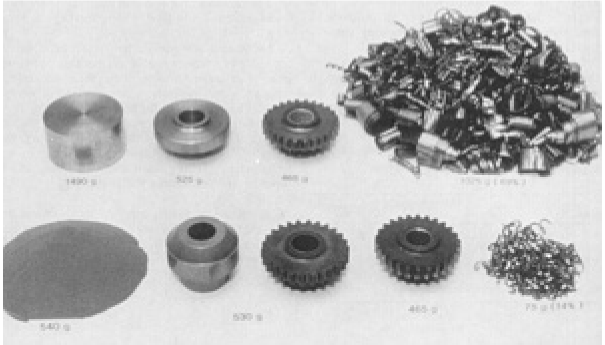


Fig. 2 Comparison of material use for a conventionally forged reverse idler gear (top) and the equivalent powder forged part (bottom). Material yield in conventional forging is 31%; that for powder forging is 86%. 1 lb = 453.6 g

In general, pore-free powder forged materials machine as readily as conventional forgings processed to achieve identical composition, structure, and hardness. Difficulties are encountered, however, if powder forged components are machined with the same cutting speeds, feed rates, and tool types as conventional components. These differences in machinability have been related to inclusion types and microporosity. Improved machinability can be accomplished by the addition of solid lubricants such as manganese sulfide.

However, the presence of microporosity and low-density noncritical areas in powder forged components leads to reduced machinability. The machinability behavior for these areas is similar to that of conventional P/M materials. The overall machinability of a powder forged component may be said to depend on the amount, type, size, shape, and dispersion of inclusions and/or porosity, as well as on the alloy and heat treated structure.

Mechanical Properties

Wrought steel bar stock undergoes extensive deformation during cogging and rolling of the original ingot. This creates inclusion stringers and leads to planes of weakness, which affect the ductile failure of the material. The mechanical properties of wrought steels vary considerably with the direction test pieces are cut from the wrought billet. Powder forged materials, on the other hand, undergo relatively little material deformation, and their mechanical properties have been shown to be relatively isotropic.

The mechanical properties of powder forged materials are usually intermediate to the transverse and longitudinal properties of wrought steels. The rotating-bending fatigue properties of powder forged materials have also been shown to fall between the longitudinal and transverse properties of wrought steel of the same tensile strength.

While the performance of machined laboratory test pieces follows the intermediate trend described above, in the case of actual components powder forged parts have been shown to have superior fatigue resistance. This has generally been attributed not only to the relative mechanical property isotropy of powder forgings, but also to their better surface finish and finer grain size.

The data presented below represent results obtained on machined standard laboratory test pieces. Data are reported for four primary materials. The first two material systems are based on prealloyed powders (P/F-4600 and P/F-4200). The third material, based on Fe-Cu-C, was used by Toyota in 1981 to make powder forged connecting rods; Ford Motor Company introduced powder forged rods with a similar chemistry in 1986. Mechanical property data are therefore presented for copper and graphite powders mixed with an iron powder base to produce materials that generally contain 2% Cu.

Heat Treatments. There were three heat treatments used in developing the properties of the prealloyed powder forged materials: case carburizing, blank carburizing, and through-hardening (quenching and tempering).

Case carburizing was applied to materials with a nominal core carbon content of 0.20 to 0.25%. Blank carburizing is intended to produce a microstructure similar to that found in the core of case carburized samples. At the 0.20 to 0.25% C level, this results in a core hardness of 45 to 55 HRC.

Quenching and tempering was applied to achieve through-hardened microstructures over a range of forged carbon contents. A low-temperature temper or stress relief at 175 °C (350 °F) resulted in core hardnesses in the range of 55 to 65 HRC for materials with carbon contents of 0.4% and above. In addition, higher-temperature tempers were designed to achieve core hardnesses of 45 to 55 HRC and 25 to 30 HRC in these higher-carbon samples.

Hardenability. Jominy hardenability curves are presented in Fig. 3 for the P/F-4600, P/F-4200, and Fe-Cu-C alloys. Testing was carried out according to ASTM A 255. Specimens were machined from upset forged billets that had been sintered at 1120 °C (2050 °F) in dissociated ammonia.

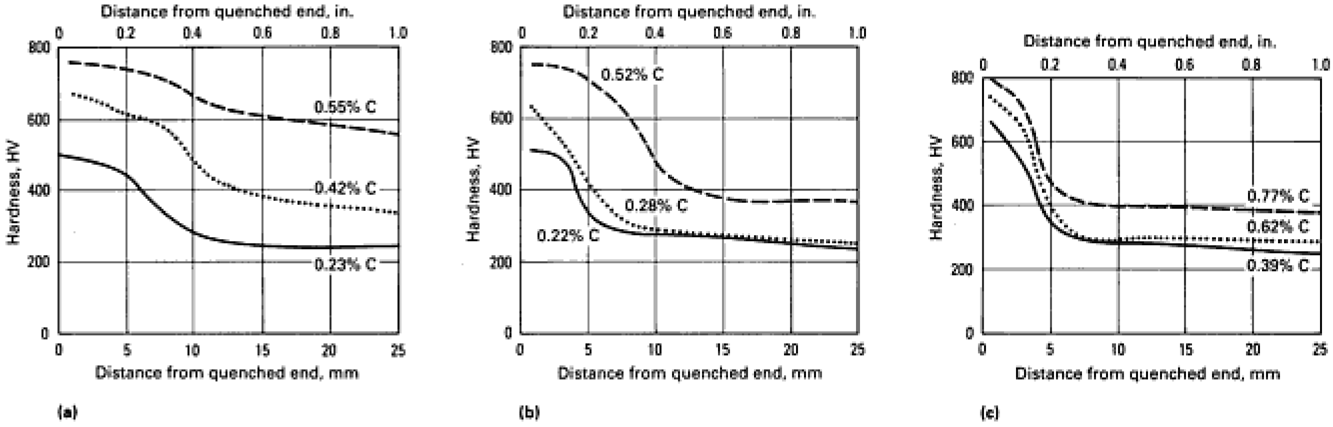


Fig. 3 Jominy hardenability curves for (a) P/F-4600, (b) P/F-4200, and (c) Fe-Cu-C materials at various forged carbon levels. Vickers hardness was determined at a 30 kgf load.

Tensile, Impact, and Fatigue Properties. Tensile properties were determined on test pieces with a gage length of 25 mm (1 in.) and a gage diameter of 6.35 mm (0.25 in.). Testing was carried out according to ASTM E 8 using a crosshead speed of 0.5 mm/min (0.02 in./min). Room-temperature impact testing was carried out on standard Charpy V-notch specimens according to ASTM E 23. Rotating-bending fatigue (RBF) testing was performed using single-load, cantilever, rotating fatigue testers. The tensile, impact, and fatigue data for the various materials are summarized in Tables 1, 2, and 3.

Table 1 Mechanical property and fatigue data for P/F-4600 materials

Sintered at 1120 °C (2050 °F) in dissociated ammonia unless otherwise noted.

Forging mode	Carbon, %	Oxygen, ppm	Ultimate tensile strength		0.2% offset yield strength		Elongation in 25 mm (1 in.), %	Reduction of area, %	Room-temperature Charpy V-notch impact energy		Core hardness, HV30	Fatigue endurance limit		Ratio of fatigue endurance to tensile strength
			MPa	**ksi**	**MPa**	**ksi**			**J**	**ft·lbf**		**MPa**	**ksi**	
Blank carburized														
Upset	0.24	230	1565	227	1425	207	13.6	42.3	16.3	12.0	487	565	82	0.36

Re-press	0.24	210	1495	217	1325	192	11.0	34.3	12.9	9.5	479	550	80	0.37
Upset[(a)]	0.22	90	1455	211	1275	185	14.8	46.4	22.2	16.4	473	550	80	0.38
Re-press[(a)]	0.25	100	1455	211	1280	186	12.5	42.3	16.8	12.4	468	510	74	0.36
Upset[(b)]	0.28	600	1585	230	1380	200	7.8	23.9	10.8	8.0	513	590	86	0.37
Re-press[(b)]	0.24	620	1580	229	1305	189	6.8	16.9	6.8	5.0	464	455	66	0.29
Quenched and stress relieved														
Upset	0.38	270	1985	288	1505	218	11.5	33.5	11.5	8.5	554	. . .	. . .	. . .
Re-press	0.39	335	1960	284	1480	215	8.5	21.0	8.7	6.4	. . .	. . .	. . .	. . .
Upset	0.57	275	2275	330	. . .	. . .	3.3	5.8	7.5	5.5	655	. . .	. . .	. . .
Re-press	0.55	305	1945	282	. . .	. . .	0.9	2.9	8.1	6.0	. . .	. . .	. . .	. . .
Upset	0.79	290	940	136	. . .	. . .	. . .	. . .	1.4	1.0	712	. . .	. . .	. . .
Re-press	0.74	280	1055	153	. . .	. . .	. . .	. . .	2.4	1.8	. . .	. . .	. . .	. . .
Upset	1.01	330	800	116	. . .	. . .	. . .	. . .	1.3	1.0	672	. . .	. . .	. . .
Re-press	0.96	375	760	110	. . .	. . .	. . .	. . .	1.6	1.2	. . .	. . .	. . .	. . .
Quenched and tempered														
Upset[(c)]	0.38	230	1490	216	1340	194	10.0	40.0	28.4	21.0	473	. . .	. . .	. . .
Re-press[(c)]	. . .	. . .	1525	221	1340	194	8.5	32.3	. . .	. . .	. . .	. . .	. . .	. . .

Upset(d)	0.60	220	1455	211	1170	170	9.5	32.0	13.6	10.0	472	. . .	. . .	. . .
Re-press(d)	. . .	. . .	1550	225	1365	198	7.0	23.0	. . .	. . .	. . .	. . .	. . .	. . .
Upset(e)	0.82	235	1545	224	1380	200	8.0	16.0	8.8	6.5	496	. . .	. . .	. . .
Re-press(e)	. . .	. . .	1560	226	1340	194	6.0	12.0	. . .	. . .	. . .	. . .	. . .	. . .
Upset(f)	1.04	315	1560	226	1280	186	6.0	11.8	9.8	7.2	476	. . .	. . .	. . .
Re-press(f)	. . .	. . .	1480	215	1225	178	6.0	11.8	. . .	. . .	. . .	. . .	. . .	. . .
Upset(g)	0.39	260	825	120	745	108	21.0	57.0	62.4	46.0	269	. . .	. . .	. . .
Upset(g)	0.58	280	860	125	760	110	20.0	50.0	44.0	32.5	270	. . .	. . .	. . .
Upset(h)	0.80	360	850	123	600	87	19.5	46.0	24.4	18.0	253	. . .	. . .	. . .
Upset(i)	1.01	320	855	124	635	92	17.0	38.0	13.3	9.8	268	. . .	. . .	. . .

(a) Sintered at 1260 °C (2300 °F) in dissociated ammonia.

(b) Sintered at 1120 °C (2050 °F) in endothermic gas atmosphere.

(c) Tempered at 370 °C (700 °F).

(d) Tempered at 440 °C (825 °F).

(e) Tempered at 455 °C (850 °F).

(f) Tempered at 480 °C (900 °F).

(g) Tempered at 680 °C (1255 °F).

(h) Tempered at 695 °C (1280 °F).

(i) Tempered at 715 °C (1320 °F)

Table 2 Mechanical property data for P/F-4200 materials

Forging mode	Carbon %	Oxygen, ppm	Ultimate tensile strength		0.2% offset yield strength		Elongation in 25 mm (1 in.), %	Reduction of area, %	Core hardness, HV30
			MPa	**ksi**	**MPa**	**ksi**			
Blank carburized									
Upset[a]	0.19	450	1205	175	. . .	. . .	10.0	37.4	390
Re-press[a]	0.23	720	1110	161	. . .	. . .	6.3	17.0	380
Upset[b]	0.25	130	1585	230	. . .	. . .	13.0	47.5	489
Re-press[b]	0.25	110	1460	212	. . .	. . .	11.3	36.1	466
Quenched and stress relieved									
Upset[a]	0.31	470	1790	260	. . .	. . .	9.0	27.3	532
Re-press[a]	0.32	700	1745	253	. . .	. . .	4.0	9.0	538
Upset[a]	0.54	380	2050	297	. . .	. . .	1.3	. . .	694
Re-press[a]	0.50	520	2160	313	. . .	. . .	2.0	. . .	653
Upset[b]	0.65	120	1605	233	. . .	. . .	. . .	. . .	710
Re-press[b]	0.67	130	1040	151	. . .	. . .	. . .	. . .	709
Upset[a]	0.73	270	1110	161	. . .	. . .	. . .	. . .	767
Re-press[a]	0.85	370	1345	195	. . .	. . .	. . .	. . .	727
Upset[a]	0.70	420	600	87	. . .	. . .	. . .	. . .	761
Re-press[a]	0.67	320	540	78	. . .	. . .	. . .	. . .	778

Upset[b]	0.91	120	910	132	. . .	. . .	. . .	. . .	820
Re-press[b]	0.86	120	840	122	. . .	. . .	. . .	. . .	825
Quenched and tempered									
Upset[c]	0.28	720	1050	153	895	130	10.6	42.8	336
Upset[b]	0.37	1200	1450	210	1385	201	10.2	33.0	447
Upset[d]	0.56	580	1680	244	7560	226	9.8	28.6	444
Upset[e]	0.70	760	1805	262	1565	227	5.0	11.8	531
Upset[f]	0.86	790	1425	207	1310	190	10.4	30.0	450
Upset[g]	0.26	920	835	121	705	102	22.6	57.6	269
Upset[h]	0.38	860	860	125	785	114	20.8	56.5	288
Upset[i]	0.55	840	917	133	820	119	17.8	49.5	305
Upset[j]	0.73	820	965	140	855	124	15.4	42.7	304
Upset[j]	0.87	920	995	144	850	123	15.6	33.9	318

(a) Sintered in dissociated ammonia at 1120 °C (2050 °F).

(b) Sintered in dissociated ammonia at 1260 °C (2300 °F).

(c) Tempered at 175 °C (350 °F).

(d) Tempered at 315 °C (600 °F).

(e) Tempered at 345 °C (650 °F).

(f) Tempered at 425 °C (800 °F).

(g) Tempered at 620 °C (1150 °F).

(h) Tempered at 650 °C (1200 °F).

(i) Tempered at 660 °C (1225 °F).

(j) Tempered at 675 °C (1250 °F)

Table 3 Mechanical property and fatigue data for iron-copper-carbon alloys

Sintered at 1120 °C (2050 °F) in dissociated ammonia, reheated to 980 °C (1800 °F), in dissociated ammonia, and forged.

Forging mode	Carbon, %	Oxygen, ppm	Ultimate tensile strength		0.2% offset yield strength		Elongation in 25 mm (1 in.), %	Reduction of area, %	Room-temperature Charpy V-notch impact energy		Core hardness, HV30	Fatigue endurance limit		Ratio of Fatigue endurance to tensile strength
			MPa	**ksi**	**MPa**	**ksi**			**J**	**ft · lbf**		**MPa**	**ksi**	
Upset[a]	0.39	250	670	97	475	69	15	37.8	4.1	3.0	228	. . .	. . .	. . .
Upset[b]	0.40	210	805	117	660	96	12.5	38.3	5.4	4.0	261	325	47	0.40
Re-press[a]	0.39	200	690	100	490	71	15	35.4	2.7	2.0	227	. . .	. . .	. . .
Re-press[b]	0.41	240	795	115	585	85	10	36.5	4.1	3.0	269	345	50	0.43
Upset[a]	0.67	170	840	122	750	109	10	22.9	2.7	2.0	267	. . .	. . .	. . .
Upset[b]	0.66	160	980	142	870	126	15	24.9	4.1	3.0	322	470	68	0.48
Re-press[a]	0.64	190	825	120	765	111	10	24.8	3.4	2.5	266	. . .	. . .	. . .
Re-press[b]	0.67	170	985	143	875	127	10	20.6	4.7	3.5	311	460	67	0.47
Upset[a]	0.81	240	1025	149	625	91	10	19.2	2.7	2.0	337	. . .	. . .	. . .
Upset[b]	0.85	280	1130	164	625	91	10	16.6	4.1	3.0	343	525	76	0.46

Re-press(a)	0.81	200	1040	151	640	93	10	16.2	2.7	2.0	335	. . .	. . .	. . .
Re-press(b)	0.82	220	1170	170	745	108	10	12.8	2.7	2.0	368	475	69	0.41

(a) Still-air cooled.

(b) Forced-air cooled

The Fe-Cu-C alloys were either still-air cooled or forced-air cooled from the austenitizing temperature of 845 °C (1550 °F). The austenitizing temperature influences core hardness. These Fe-Cu-C alloys are often used with manganese sulfide additions for enhanced machinability. The tensile, impact, and fatigue properties for a sample with a 0.35% manganese sulfide addition are compared with a material without sulfide additions in Table 4. Data from the samples with manganese sulfide and sulfurized powders are included for comparison. The manganese sulfide addition had little influence on tensile strength, whereas the sulfurization process degraded tensile properties.

Table 4 Mechanical property and fatigue data for iron-copper-carbon alloys with sulfur additions

Sintered at 1120 °C (2050 °F) in dissociated ammonia, reheated to 980 °C (1800 °F) in dissociated ammonia, and forged.

Addition	Carbon, %	Oxygen, ppm	Sulfur, %	Ultimate tensile strength		0.2% offset yield strength		Elongation in 25 mm (1 in.), %	Reduction of area, %	Room-temperature Charpy V-notch impact energy		Core hardness, HV30	Fatigue endurance limit		Ratio of fatigue endurance to tensile strength
				MPa	**ksi**	**MPa**	**ksi**			**J**	**ft · lbf**		**MPa**	**ksi**	
Manganese sulfide	0.59	270	0.13	915	133	620	90	11	23.2	6.8	5.0	290	430	62	0.47
Sulfur	0.63	160	0.14	840	122	560	81	12	21.4	6.8	5.0	267	415	60	0.50
None	0.66	160	0.013	980	142	870	126	15	24.9	4.1	3.0	322	470	68	0.48

Effect of Porosity on Mechanical Properties. The mechanical property data summarized in the previous sections are related to either hot re-press or hot upset forged pore-free material. The general effect of density on mechanical properties is presented in Table 5.

Table 5 Tensile and impact properties of P/F-4600 hot re-pressed at two temperatures

Re-pressing temperature		Re-pressing stress		Re-pressed density		0.2% offset yield strength		Ultimate tensile strength		Elongation, %	Reduction in area, %	Hardness, HV30	Charpy V-notch impact energy	
°C	**°F**	**MPa**	**ksi**	**g/cm^3**	**lb/in.^3**	**MPa**	**ksi**	**MPa**	**ksi**				**J**	**ft · lbf**
870	1600	406	59	7.65	0.276	1156	168	1634	237	2.6	2.8	519	2.9	2.13
870	1600	565	82	7.72	0.279	1243	180	1641	238	2.1	2.8	538	2.8	2.06
870	1600	741	107	7.78	0.281	1316	191	1702	247	2.4	2.4	564	3.1	2.29
870	1600	943	137	7.79	0.282	1349	196	1705	248	2.3	2.4	562	3.5	2.58
1120	2050	344	50	7.83	0.283	1364	198	1750	254	6.4	20.5	549	6.8	5.01
1120	2050	593	86	7.86	0.2840	1450	210	1777	258	6.7	17.3	566	6.2	4.57
1120	2050	856	124	7.87	0.2844	1592	231	1782	259	5.3	14.1	565	6.2	4.57
1120	2050	981	142	7.87	0.2844	1502	218	1788	260	5.5	12.3	572	6.0	4.42

Metal Injection Molding

Processing Steps. The metal injection molding (MIM) process combines the structural benefits of metallic materials with the shape complexity of plastic injection molding technology. A uniform mixture of powder and binders is prepared and injected into a mold. The MIM powders are typically spherical in shape and much finer in particle size than those used for conventional cold-die compaction (MIM powder, 10 to 20 μm; conventional die-compaction powders, 50 to 150 μm). The binders are formulated specially to provide the proper rheological properties during injection molding as well as ease of binder removal after the molding step. Once the part is ejected from the mold, the binder material is removed using either solvent extraction or thermal processes (or both). After the debinding step the part is then sintered to complete the process. Sintering temperatures are usually in excess of 1260 °C (2300 °F). Due to the large amount of binder in the MIM starting material (up to 40% by volume), the MIM part undergoes a large reduction in size (as much as 20% linear shrinkage) during sintering. Dimensional tolerances, therefore, are not as good as in conventional die compaction and a straightening or coinciding step is sometimes needed.

Cost Considerations. Due to the high cost of the raw materials (carbonyl iron and binder), the MIM process is more expensive than conventional press-and-sinter methods. However, the capital equipment (presses) for injection molding is more economical than that for large-scale P/M presses. Tool life is at least 300,000 pieces. These factors help offset the added short-term material cost.

Compositions and Properties. Table 6 lists the compositions of powders used for producing low-alloy steels. Both prealloyed powders and admixtures of iron powder and alloying elements such as nickel, molybdenum, and carbon are employed.

Table 6 Chemical compositions of MIM low-alloy steels

Material designation	Composition (min to max), wt %				
	Fe	**Ni**	**Mo**	**C**	**Other**
MIM-4600	94.90-98.50	1.5-2.5	0.0-0.5	0.0-0.1	0.0-2.0
MIM-4650	94.40-98.10	1.5-2.5	0.0-0.5	0.4-0.6	0.0-2.0

Depending on the fineness of the starting powder and the sintering temperature, densities of 93 to 98% of full density are obtained. Minimum and typical mechanical property values for 95 and 96% dense MIM low-alloy steels are given in Table 7. As these data indicate, ductility of MIM-processed parts is very high, with elongation values of 30% or higher.

Table 7 Mechanical properties of MIM low-alloy steels

Material designation/condition	Minimum values					Typical values						
	Ultimate tensile strength		**0.2% yield strength**		**Elongation in 25 mm (1 in.), %**	**Ultimate tensile strength**		**0.2% yield strength**		**Elongation in 25 mm (1 in.), %**	**Density, g/cm^3**	**Apparent hardness(a)**
	MPa	**ksi**	**MPa**	**ksi**		**MPa**	**ksi**	**MPa**	**ksi**			
MIM-4600 as-sintered	255	37	110	16	20.0	290	42	125	18	40	7.6	45 HRB
MIM-4650 as-sintered	380	55	170	25	11.0	440	64	205	30	15	7.5	62 HRB
MIM-4650 quenched and tempered	1480	215	1310	190	<1.0	1655	240	1480	215	2	7.5	48 HRC (55 HRC) (55 HRC)
MIM-2700 as-sintered	380	55	205	30	20.0	415	60	255	37	26	7.6	69 HRB

Source: MPIF Standard 35, Materials Standards for Metal Injection Molded Parts, 1993-1994 edition

(a) Where applicable, the matrix (converted) hardness is also given in parentheses.

Figure 4(a), a photomicrograph of an unetched specimen of low-carbon iron plus 2% Ni steel illustrates the typical pore structure of injection molded parts. With the very small powders used, the pores remain small and isolated, with no interconnected porosity. Figure 4(b) shows the same field in the etched condition, displaying the typical enlargement of pores obtained by etching. There is no evidence of the presence of the original metal particles in the ferritic structure.

Because the interconnected porosity is so low (or absent), parts do not have to be resin impregnated prior to plating and close control over case depths is possible in carburizing.

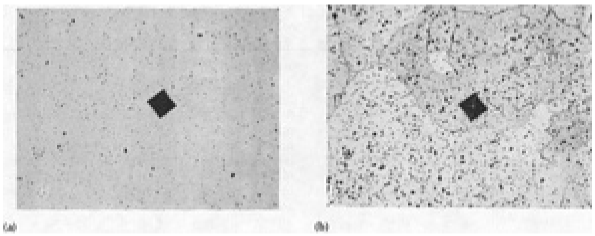


Fig. 4 Small, well-distributed, rounded pores in a MIM-processed nickel steel (97% density). (a) Unetched. 100×. (b) Etched with 10% ammonium persulfate. Shows ferrite with grain boundaries. 100×

Tool Steels

Introduction

A TOOL STEEL is any steel used to make tools for cutting, forming, or otherwise shaping a material into a part or component adapted to a definite use. The earliest tool steels were simple, plain carbon steels, but by 1868 and increasingly in the early 20th century, many complex, highly alloyed tool steels were developed. These tool steels contain, among other elements, relatively large amounts of tungsten, molybdenum, vanadium, manganese, and chromium, and they make it possible to meet increasingly severe service demands and to provide greater dimensional control and freedom from cracking during heat treatment. Many alloy tool steels are also used for machinery components and structural applications in which particularly stringent requirements must be met, such as high-temperature springs, ultrahigh-strength fasteners, special-purpose valves, and bearings of various types for elevated-temperature service.

In service, most tools are subjected to extremely high loads that are applied rapidly. The tools must withstand these loads a great number of times without breaking and without undergoing excessive wear or deformation. In many applications, tool steels must provide this capability under conditions that produce high temperatures in the tool. No single tool material combines maximum wear resistance, toughness, and resistance to softening at elevated temperatures. Consequently, the selection of the proper tool material for a given application often requires a trade-off to achieve the optimal combination of properties.

Most tool steels are wrought products, but precision castings can be used to advantage in some applications. Powder metallurgy processing is also used in making tool steels. It provides, first, a more uniform carbide size and distribution in large sections and, second, special compositions that are difficult or impossible to produce by melting and casting and then mechanically working the cast product.

For typical wrought tool steels, raw materials (including scrap) are carefully selected not only for alloy content but also for qualities that ensure cleanliness and homogeneity in the finished product. Tool steels are generally melted in relatively small-tonnage electric arc furnaces to economically achieve composition tolerances, cleanliness, and precise control of melting conditions. Special ladle refining and secondary remelting processes such as electroslag remelting and vacuum arc remelting have been introduced to satisfy particularly stringent demands regarding tool steel quality and performance. The medium to high alloy contents of many tool steels require careful control of forging and rolling, which often results in a large amount of process scrap. Semifinished and finished bars are given rigorous in-process and final inspections. These inspections can be so extensive that both ends of each bar may be inspected for macrostructure (etch quality), cleanliness, hardness, grain size, annealed structure, and hardening ability. The inspections may also require that the entire bar be subjected to magnetic and ultrasonic inspections for surface and internal discontinuities. It is important that finished tool steel bars have minimal decarburization within carefully controlled limits, which requires that annealing be done by special procedures under closely controlled conditions.

Such precise production practices and stringent quality controls contribute to the high cost of tool steels, as do the expensive alloying elements they contain. Insistence on quality in the manufacture of these specialty steels is justified, however, because tool steel bars generally are made into complicated cutting and forming tools worth many times the cost of the steel itself. Although some standard constructional alloy steels resemble tool steels in composition, they are seldom used for expensive tooling because in general they are not manufactured to the same rigorous quality standards as are tool steels.

The performance of a tool in service depends on proper design of the tool, the accuracy with which the tool is made, selection of the property tool steel, and application of the proper heat treatment. A tool can perform successfully in service only when all four of these requirements have been met.

Classification and Characteristics

Table 1 gives composition limits for the wrought tool steels most commonly used. Each group of tool steels of similar composition and properties is identified by a capital letter; within each group, individual tool steel types are assigned code numbers.

Table 1 Composition limits of principal types of tool steels

Designation		Composition[(a)], %								
AISI	**UNS**	**C**	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**W**	**V**	**Co**
Molybdenum high-speed steels										
M1	T11301	0.78-0.88	0.15-0.40	0.20-0.50	3.50-4.00	0.30 max	8.20-9.20	1.40-2.10	1.00-1.35	. . .
M2	T11302	0.78-0.88; 0.95-1.05	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	5.50-6.75	1.75-2.20	. . .
M3, class 1	T11313	1.00-1.10	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.75-6.50	5.00-6.75	2.25-2.75	. . .
M3, class 2	T11323	1.15-1.25	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.75-6.50	5.00-6.75	2.75-3.75	. . .
M4	T11304	1.25-1.40	0.15-0.40	0.20-0.45	3.75-4.75	0.30 max	4.25-5.50	5.25-6.50	3.75-4.50	. . .
M7	T11307	0.97-1.05	0.15-0.40	0.20-0.55	3.50-4.00	0.30 max	8.20-9.20	1.40-2.10	1.75-2.25	. . .
M10	T11310	0.84-0.94; 0.95-1.05	0.10-0.40	0.20-0.45	3.75-4.50	0.30 max	7.75-8.50	. . .	1.80-2.20	. . .
M30	T11330	0.75-0.85	0.15-0.40	0.20-0.45	3.50-4.25	0.30 max	7.75-9.00	1.30-2.30	1.00-1.40	4.50-5.50

M33	T11333	0.85-0.92	0.15-0.40	0.15-0.50	3.50-4.00	0.30 max	9.00-10.00	1.30-2.10	1.00-1.35	7.75-8.75
M34	T11334	0.85-0.92	0.15-0.40	0.20-0.45	3.50-4.00	0.30 max	7.75-9.20	1.40-2.10	1.90-2.30	7.75-8.75
M35	T11335	0.82-0.88	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.50-5.50	5.50-6.75	1.75-2.20	4.50-5.50
M36	T11336	0.80-0.90	0.15-0.40	0.20-0.45	3.75-4.50	0.30 max	4.58-5.50	5.50-6.50	1.75-2.25	7.75-8.75
M41	T11341	1.05-1.15	0.20-0.60	0.15-0.50	3.75-4.50	0.30 max	3.25-4.25	6.25-7.00	1.75-2.25	4.75-5.75
M42	T11342	1.05-1.15	0.15-0.40	0.15-0.65	3.50-4.25	0.30 max	9.00-10.00	1.15-1.85	0.95-1.35	7.75-8.75
M43	T11343	1.15-1.25	0.20-0.40	0.15-0.65	3.50-4.25	0.30 max	7.50-8.50	2.25-3.00	1.50-1.75	7.75-8.75
M44	T11344	1.10-1.20	0.20-0.40	0.30-0.55	4.00-4.75	0.30 max	6.00-7.00	5.00-5.75	1.85-2.20	11.00-12.25
M46	T11346	1.22-1.30	0.20-0.40	0.40-0.65	3.70-4.20	0.30 max	8.00-8.50	1.90-2.20	3.00-3.30	7.80-8.80
M47	T11347	1.05-1.15	0.15-0.40	0.20-0.45	3.50-4.00	0.30 max	9.25-10.00	1.30-1.80	1.15-1.35	4.75-5.25
M47	T11348	1.42-1.52	0.15-0.40	0.15-0.40	3.50-4.00	0.30 max	4.75-5.50	9.50-10.50	2.75-3.25	8.00-10.00
M62	T11362	1.25-1.35	0.15-0.40	0.15-0.40	3.50-4.00	0.30 max	10.00-11.00	5.75-6.50	1.80-2.10	. . .
Tungsten high-speed steels										
T1	T12001	0.65-0.80	0.10-0.40	0.20-0.40	3.75-4.50	0.30 max	. . .	17.25-18.75	0.90-1.30	. . .
T2	T12002	0.80-0.90	0.20-0.40	0.20-0.40	3.75-4.50	0.30 max	1.0 max	17.50-19.00	1.80-2.40	. . .
T4	T12004	0.70-0.80	0.10-0.40	0.20-0.40	3.75-4.50	0.30 max	0.40-1.00	17.50-19.00	0.80-1.20	4.25-5.75

T5	T12005	0.75-0.85	0.20-0.40	0.20-0.40	3.75-5.00	0.30 max	0.50-1.25	17.50-19.00	1.80-2.40	7.00-9.50
T6	T12006	0.75-0.85	0.20-0.40	0.20-0.40	4.00-4.75	0.30 max	0.40-1.00	18.50-21.00	1.50-2.10	11.00-13.00
T8	T12008	0.75-0.85	0.20-0.40	0.20-0.40	3.75-4.50	0.30 max	0.40-1.00	13.25-14.75	1.80-2.40	4.25-5.75
T15	T12015	1.50-1.60	0.15-0.40	0.15-0.40	3.75-5.00	0.30 max	1.00 max	11.75-13.00	4.50-5.25	4.75-5.25
Intermediate high-speed steels										
M50	T11350	0.78-0.88	0.15-0.45	0.20-0.60	3.75-4.50	0.30 max	3.90-4.75	. . .	0.80-1.25	. . .
M52	T11352	0.85-0.95	0.15-0.45	0.20-0.60	3.50-4.30	0.30 max	4.00-4.90	0.75-1.50	1.65-2.25	. . .
Chromium hot-work steels										
H10	T20810	0.35-0.45	0.25-0.70	0.80-1.20	3.00-3.75	0.30 max	2.00-3.00	. . .	0.25-0.75	. . .
H11	T20811	0.33-0.43	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.10-1.60	. . .	0.30-0.60	. . .
H12	T20812	0.30-0.40	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.25-1.75	1.00-1.70	0.50 max	. . .
H13	T20813	0.32-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	1.10-1.75	. . .	0.80-1.20	. . .
H14	T20814	0.35-0.45	0.20-0.50	0.80-1.20	4.75-5.50	0.30 max	. . .	4.00-5.25	. . .	. . .
H19	T20819	0.32-0.45	0.20-0.50	0.20-0.50	4.00-4.75	0.30 max	0.30-0.55	3.75-4.50	1.75-2.20	4.00-4.50
Tungsten hot-work steels										
H21	T20821	0.28-0.36	0.15-0.40	0.15-0.50	3.00-3.75	0.30 max	. . .	8.50-10.00	0.30-0.60	. . .
H22	T20822	0.30-0.40	0.15-	0.15-	1.75-3.75	0.30	. . .	10.00-	0.25-0.50	. . .

			0.40	0.40		max		11.75		
H23	T20823	0.25-0.35	0.15-0.40	0.15-0.60	11.00-12.75	0.30 max	. . .	11.00-12.75	0.75-1.25	. . .
H24	T20824	0.42-0.53	0.15-0.40	0.15-0.40	2.50-3.50	0.30 max	. . .	14.00-16.00	0.40-0.60	. . .
H25	T20825	0.22-0.32	0.15-0.40	0.15-0.40	3.75-4.50	0.30 max	. . .	14.00-16.00	0.40-0.60	. . .
H26	T20826	0.45-0.55(b)	0.15-0.40	0.15-0.40	3.75-4.50	0.30 max	. . .	17.25-19.00	0.75-1.25	. . .
Molybdenum hot-work steels										
H42	T20842	0.55-0.70(b)	0.15-0.40	. . .	3.75-4.50	0.30 max	4.50-5.50	5.50-6.75	1.75-2.20	. . .
Air-hardening, medium-alloy, cold-work steels										
A2	T30102	0.95-1.05	1.00 max	0.50 max	4.75-5.50	0.30 max	0.90-1.40	. . .	0.15-0.50	. . .
A3	T30103	1.20-1.30	0.40-0.60	0.50 max	4.75-5.50	0.30 max	0.90-1.40	. . .	0.80-1.40	. . .
A4	T30104	0.95-1.05	1.80-2.20	0.50 max	0.90-2.20	0.30 max	0.90-1.40	. . .	. . .	. . .
A6	T30106	0.65-0.75	1.80-2.50	0.50 max	0.90-1.20	0.30 max	0.90-1.40	. . .	. . .	. . .
A7	T30107	2.00-2.85	0.80 max	0.50 max	5.00-5.75	0.30 max	0.90-1.40	0.50-1.50	3.90-5.15	. . .
A8	T30108	0.50-0.60	0.50 max	0.75-1.10	4.75-5.50	0.30 max	1.15-1.65	1.00-1.50	. . .	. . .
A9	T30109	0.45-0.55	0.50 max	0.95-1.15	4.75-5.50	1.25-1.75	1.30-1.80	. . .	0.80-1.40	. . .
A10	T30110	1.25-1.50(c)	1.60-2.10	1.00-1.50	. . .	1.55-2.05	1.25-1.75	. . .	. . .	. . .
High-carbon, high-chromium, cold-work steels										

D2	T30402	1.40-1.60	0.60 max	0.60 max	11.00-13.00	0.30 max	0.70-1.20	. . .	1.10 max	. . .
D3	T30403	2.00-2.35	0.60 max	0.60 max	11.00-13.50	0.30 max	. . .	1.00 max	1.00 max	. . .
D4	T30404	2.05-2.40	0.60 max	0.60 max	11.00-13.00	0.30 max	0.70-1.20	. . .	1.00 max	. . .
D5	T30405	1.40-1.60	0.60 max	0.60 max	11.00-13.00	0.30 max	0.70-1.20	. . .	1.00 max	2.50-3.50
D7	T30407	2.15-2.50	0.60 max	0.60 max	11.50-13.50	0.30 max	0.70-1.20	. . .	3.80-4.40	. . .
Oil-hardening cold-work steels										
O1	T31501	0.85-1.00	1.00-1.40	0.50 max	0.40-0.60	0.30 max	. . .	0.40-0.60	0.30 max	. . .
O2	T31502	0.85-0.95	1.40-1.80	0.50 max	0.50 max	0.30 max	0.30 max	. . .	0.30 max	. . .
O6	T31506	1.25-1.55(c)	0.30-1.10	0.55-1.50	0.30 max	0.30 max	0.20-0.30	. . .	. . .	. . .
07	T31507	1.10-1.30	1.00 max	0.60 max	0.35-0.85	0.30 max	0.30 max	1.00-2.00	0.40 max	. . .
Shock-resisting steels										
S1	T41901	0.40-0.55	0.10-0.40	0.15-1.20	1.00-1.80	0.30 max	0.50 max	1.50-3.00	0.15-0.30	. . .
S2	T41902	0.40-0.55	0.30-0.50	0.90-1.20	. . .	0.30 max	0.30-0.60	. . .	0.50 max	. . .
S5	T41905	0.50-0.65	0.60-1.00	1.75-2.25	0.50 max	. . .	0.20-1.35	. . .	0.35 max	. . .
S6	T41906	0.40-0.50	1.20-1.50	2.00-2.50	1.20-1.50	. . .	0.30-0.50	. . .	0.20-0.40	. . .
S7	T41907	0.45-0.55	0.20-0.90	0.20-1.00	3.00-3.50	. . .	1.30-1.80	. . .	0.20-0.30(d)	. . .

Low-alloy special-purpose tool steels										
L2	T61202	0.45-1.00[b]	0.10-0.90	0.50 max	0.70-1.20	. . .	0.25 max	. . .	0.10-0.30	. . .
L6	T61206	0.65-0.75	0.25-0.80	0.50 max	0.60-1.20	1.25-2.00	0.50 max	. . .	0.20-0.30[d]	. . .
Low-carbon mold steels										
P2	T51602	0.10 max	0.10-0.40	0.10-0.40	0.75-1.25	0.10-0.50	0.15-0.40	. . .	. . .	. . .
P3	T51603	0.10 max	0.20-0.60	0.40 max	0.40-0.75	1.00-1.50	. . .	. . .	. . .	. . .
P4	T51604	0.12 max	0.20-0.60	0.10-0.40	4.00-5.25	. . .	0.40-1.00	. . .	. . .	. . .
P5	T51605	0.10 max	0.20-0.60	0.40 max	2.00-2.50	0.35 max	. . .	. . .	. . .	. . .
P6	T51606	0.05-0.15	0.35-0.70	0.10-0.40	1.25-1.75	3.25-3.75	. . .	. . .	. . .	. . .
P20	T51620	0.28-0.40	0.60-1.00	0.20-0.80	0.40-2.00	. . .	0.30-0.55	. . .	. . .	. . .
P21	T51621	0.18-0.22	0.20-0.40	0.20-0.40	0.50 max	3.90-4.25	. . .	. . .	0.15-0.25	1.05-1.25A1
Water-hardening tool steels										
W1	T72301	0.70-1.50[e]	0.10-0.40	0.10-0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	. . .
W2	T72302	0.85-1.50[e]	0.10-0.40	0.10-0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.15-0.35	. . .
W3	T72305	1.05-1.15	0.10-0.40	0.10-0.40	0.40-0.60	0.20 max	0.10 max	0.15 max	0.10 max	. . .

(a) All steels except group W contain 0.25 max Cu, 0.03 max P, and 0.03 max S; group W contains 0.20 max Cu, 0.025 max P, and 0.025 max S. Where specified, sulfur may be increased to 0.06 to 0.15% to improve machinability of group A, D, H, M, and T steels.

(b) Available in several carbon ranges.

(c) Contains free graphite in the microstructure.

(d) Optional.

(e) Specified carbon ranges are designated by suffix numbers.

Tool steels are produced to various standards, including several ASTM specifications. The Steel Products Manual covering tool steels, which is published by the Iron and Steel Society, Inc. (Ref 1), contains much useful information that essentially represents the normal manufacturing practices of most tool steel producers. Frequently, more stringent chemical and/or metallurgical standards are invoked by the individual producers or consumers to achieve certain commercial goals. Where appropriate, standard specifications for tool steels, ASTM A600, A681, and A686, may be used as a basis for procurement. ASTM A600 sets forth standard requirements for tungsten and molybdenum high-speed steels; A681 is application to hot-work, cold-work, shock-resisting, special-purpose, and mold steels; and A686 covers water-hardening tool steels. In many instances, however, tool steels are purchased by tradename because the user has found that a particular tool steel from a certain producer gives better performance in a specific application than does a tool steel of the same AISI type classification purchased from another source.

High-Speed Steels

High-speed steels are tool materials developed largely for use in high-speed cutting tool applications. There are two classifications of high-speed steels; molybdenum high-speed steels, also called group M, and tungsten high-speed steels, also called group T. Group M steels constitute more than 95% of all high-speed steel produced in the United States. A subgroup in the M group consists of intermediate high-speed steels.

Group M and group T high-speed steels are equivalent in performance. The main advantage of the group M steels is lower initial cost (approximately 40% lower than that of similar group T steels).

Molybdenum high-speed steels and tungsten high-speed steels are similar in many other respects, including hardening ability. Typical applications for both categories including cutting tools of all sorts, such as drills, reamers, end mills, milling cutters, taps, and hobs. Some grades are satisfactory for cold-work applications, such as cold-header die inserts, thread-rolling dies, punches, and blanking dies. Steels of the M40 series are used to make cutting tools for machining modern, very tough, high-strength steels. Additional information on the use of high-speed steels for cutting tools can be found in the Section "Machining" in this Handbook.

Molybdenum high-speed steels contain molybdenum, tungsten, chromium, vanadium, cobalt, and carbon as principal alloying elements. Group M steels have slightly greater toughness than group T steels at the same hardness. Otherwise, mechanical properties of the two groups are similar.

Increasing the carbon and vanadium contents of group M steels increases wear resistance. Increasing the cobalt content improves red (hot) hardness (that is, the capability of certain steels to resist softening at temperatures high enough to cause the steel to emit radiation in the red part of the visible spectrum), but it simultaneously lowers toughness. Type M2 and other grades in the M group have unusually high resistance to softening at elevated temperatures as a result of high alloy content (Fig. 1).

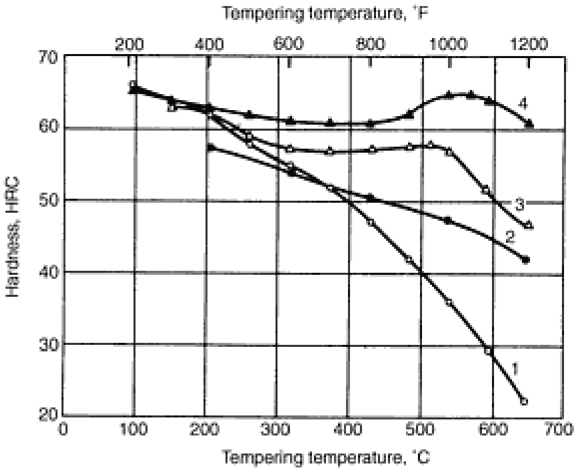


Fig. 1 Variation of hardness with tempering temperature for four typical tool steels. Curves are for 1 h at temperature. Curve 1 illustrates low resistance to softening as tempering temperatures increases, such as exhibited by group W and group O steels. Curve 2 illustrates medium resistance to softening, such as exhibited by type S1 tool steel. Curves 3 and 4 illustrate high and very high resistance to softening, respectively, such as are exhibited by the secondary hardening tool steels A2 and M2.

Group M steels readily decarburize and can be damaged from overheating under adverse austenitizing environments, so they are more sensitive than group T steels to hardening conditions, particularly austenitizing temperature and atmosphere. This is especially true of high-molybdenum, low-tungsten compositions.

Group M high-speed steels are deep hardening. They must be austenitized at temperatures lower than those for hardening group T steels to avoid incipient melding. Group M high-speed steels can develop full hardness when quenched from temperatures of 1175 to 1230 °C (2150 to 2250 °F).

The maximum hardness that can be obtained in group M high-speed steels varies with composition. For those with lower carbon contents, that is, types M1, M2, M10 (low-carbon composition), M30, M33, M34, and M36, maximum hardness is usually 65 HRC. For higher carbon contents, including types M3, M4, and M7, maximum hardness is about 66 HRC. Maximum hardness of the higher-carbon, cobalt-containing steels, that is, types M41, M42, M43, M44, and M46, is 69 to 70 HRC. However, few industrial applications exist for steels of the M40 series at this maximum hardness. Usually, the heat treatment is adjusted to provide a hardness of 66 to 68 HRC.

Tungsten high-speed steels contain tungsten, chromium, vanadium, cobalt, and carbon as the principal alloying elements. Type T1 was developed partly as a result of the work of Taylor and White, who found in the early 1900s that certain steels with more than 14% W, about 4% Cr, and about 0.3% V exhibited red hardness. In its earliest form, type T1 contained about 0.68% C, 18% W, 4% Cr, and 0.3% V. By 1920, the vanadium content had been increased to about 1.0%. Over the years, the carbon content was gradually increased to its present level, for most steels, of approximately 0.75%.

Group T high-speed steels are characterized by high red hardness and wear resistance. They are so deep hardening that sections up to 75 mm (3 in.) in thickness or diameter can be hardened to 65 HRC or more by quenching in oil or molten salt. The high alloy and high carbon contents produce a large number of hard, wear-resistant carbides in the microstructure, particularly in types containing more than 1.5% V and more than 1.0% C. Type T15, which contains approximately 1.55% C, is the most wear-resistant steel of this group.

The combination of good wear resistance and high red hardness makes group T high-speed steels suitable for many high-performance cutting tool applications. Their toughness allows them to outperform cemented carbides in delicate tools and interrupted-cut applications. Group T high-speed steels are primarily used for cutting tools such as bits, drills, reamers, taps, broaches, milling cutters, and hobs. These steels are also used for making dies, punches, and high-load, high-temperature structural components such as aircraft bearings and pump parts.

Group T high-speed steels are all deep hardening when quenched from their recommended hardening temperature of 1205 to 1300 °C (2200 to 2375 °F). They are seldom used to make hardened tools with section sizes greater than 75 mm (3 in.).

Even very large cutting tools, such as drills 75 and 100 mm (3 and 4 in.) in diameter, have relatively small effective sections for hardening. Some large-diameter solid tools are made from group T high-speed steels, including broaches and cold extrusion punches as large as 100 to 125 mm (4 to 5 in.) in diameter.

The difference between surface hardness and center hardness varies with bar size. The section size and total mass of a given tool often have an effect on its response to a given hardening treatment that is equal to or greater than the effect of the grade of tool steel selected. For tools of extremely large diameter or heavy section, it is relatively common practice to use an accelerated oil quench to provide full hardness. This practice may yield values of Rockwell C hardness only one or two points higher than those obtainable through hot salt quenching or air cooling (which ordinarily produce full hardness in tools smaller than about 75 mm, or 3 in., in diameter) but at such high hardnesses that the increase in Rockwell hardness may prove quite significant.

The maximum hardness of tungsten high-speed steels varies with carbon content and, to a lesser degree, with alloy content. A hardness of at least 64.5 HRC can be developed in any high-speed steel. Those types that have high carbon contents and high carbides, such as T15, may be hardened to 67 HRC.

Hot-Work Steels

Many manufacturing operations involve punching, shearing, or forming of metals at high temperatures. Hot-work steels (group H) have been developed to withstand the combinations of heat, pressure, and abrasion associated with such operations.

Group H tool steels usually have medium carbon contents (0.35 to 0.45%) and chromium, tungsten, molybdenum, and vanadium contents of 6 to 25%. These steels are divided into three subgroups: chromium hot-work steels (types H10 to H19), tungsten hot-work steels (types H21 to H26), and molybdenum hot-work steels (types H42 and H43).

Chromium hot-work steels (types H10 to H19) have good resistance to heat softening because of their medium chromium content and the addition of carbide-forming elements such as molybdenum, tungsten, and vanadium. The low carbon and low total alloy contents promote toughness at the normal working hardnesses of 40 to 55 HRC. Higher tungsten and molybdenum contents increase hot strength but slightly reduce toughness. Vanadium is added to increase resistance to washing (erosive wear) at high temperatures. An increase in silicone content improves oxidation resistance at temperatures up to 800 °C (1475 °F). The most widely used types in this group are H11, H12, H13, and, to a lesser extent, H19.

All of the chromium hot-work steels are deep hardening. The H11, H12, and H13 steels may be air hardened to full working hardness in section sizes up to 150 mm (6 in.); other group H steels may be air hardened in section sizes up to 305 mm (12 in.). The air-hardening qualities and balanced alloy contents of these steels result in low distortion during hardening. Chromium hot-work steels are especially well adapted to hot die work of all kinds, particularly dies for the extrusion of aluminum and magnesium, as well as die casting dies, forging dies, mandrels, and hot shears. Most of these steels have alloy and carbon contents low enough that tools made from them can be water cooled in service without cracking.

Tool steel H11 and modifications of this alloy are used to make certain highly stressed structural parts, particularly in aerospace technology. Material for such demanding applications is produced by vacuum arc remelting, which provides extremely low residual-gas content, excellent microcleanliness, and a high degree of structural homogeneity.

The chief advantage of H11 over conventional high-strength steels is its ability to resist softening during continued exposure to temperatures up to 540 °C (1000 °F) and at the same time provide moderate toughness and ductility at room-temperature tensile strengths of 1720 to 2070 MPa (250 to 300 ksi). In addition, because of its secondary hardening characteristic, H11 can be tempered at high temperatures, resulting in nearly complete relief of residual hardening stresses, which is necessary for maximum toughness at high strength levels. Other important advantages of H11, H12, and H13 steels for structural and hot-work applications include ease of forming and working, good weldability, relatively low coefficient of thermal expansion, acceptable thermal conductivity, and above-average resistance to oxidation and corrosion.

Tungsten Hot-Work Steels. The principal alloying elements of tungsten hot-work steels (types H21 to H26) are carbon, tungsten, chromium, and vanadium. The higher alloy contents of these steels make them more resistant to high-temperature softening and washing than H11 and H13 hot-work steels. However, high alloy content also makes them more prone to brittleness at normal working hardnesses (45 to 55 HRC) and makes it difficult for them to be safely water cooled in service.

Although tungsten hot-work steels can be air hardened, they are usually quenched in oil or hot salt to minimize scaling. When air hardened, they exhibit low distortion. Tungsten hot-work steels require higher hardening temperatures than chromium hot-work steels, making the former more likely to scale when heated in an oxidizing atmosphere.

Although these steels have much greater toughness, in many characteristics they are similar to high-speed steels. In fact, type H26 is a low-carbon version of T1 high-speed steel. If tungsten hot-work steels are preheated to operating temperature before use, breakage can be minimized. These steels have been used to make mandrels and extrusion dies for high-temperature applications, such as the extrusion of brass, nickel alloys, and steel, and they are also suitable for use in hot-forging dies of rugged design.

Molybdenum Hot-Work Steel. There are only two active molybdenum hot-work steels: type H42 and type H43. These alloys contain molybdenum, chromium, vanadium, carbon, and varying amounts of tungsten. They are similar to tungsten hot-work steels, having almost identical characteristics and uses. Although their compositions resemble those of various molybdenum high-speed steels, they have a low carbon content and greater toughness. The principal advantage of types H42 and H43 over tungsten hot-work steels is their lower initial cost. They are more resistant to heat checking than are tungsten hot-work steels, but in common with all high-molybdenum steels, they require greater care in heat treatment, particularly with regard to decarburization and control of austenitizing temperature.

Proprietary Hot-Work Tool Steels

There are a number of proprietary low-alloy steel grades that are used for hot forging die holders and die blocks. As listed in Table 2, the principal alloying elements in these steels are nickel, molybdenum, and chromium, with vanadium and silicon in smaller additions. The total alloying content is generally small enough that adequate machinability is retained in prehardened die blocks of these grades. Characterized by high toughness and, in some instances, by good heat resistance, these steels have very good hardenability. As a trade-off to their good toughness, the are generally heat treated to relatively low hardnesses. Because of these low hardnesses, their wear resistance is only moderate. However, they are known to possess good resistance to shock loading (such as encountered in hammer forging), heat checking, and catastrophic failure.

Table 2 Nominal compositions of proprietary low-alloy hot-work tool steels

Steel[a]	Composition, wt%						
	C	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**V**
6G	0.55	0.80	0.25	1.00	. . .	0.45	0.10
6F2	0.55	0.75	0.25	1.00	1.00	0.30	0.10[b]
6F3	0.55	0.60	0.85	1.00	1.80	0.75	0.10[b]
6F4	0.20	0.70	0.25	. . .	3.00	3.35	. . .
6F5	0.55	1.00	1.00	0.50	2.70	0.50	0.10
6F6	0.50	. . .	1.50	1.50	. . .	0.20	. . .
6F7	0.40	0.35	. . .	1.50	4.25	0.75	. . .

6H1	0.55	. . .	. . .	4.00	. . .	0.45	0.85
6H2	0.55	0.40	1.10	5.00	1.50	1.50	1.00

(a) The designations of these steels represent a continuation of those used in the 1948 Metals Handbook, except that they were previously written in Roman numerals (VIF2, etc.). Neither AISI or SAE has assigned type numbers to these tool steels, compositions of which may vary slightly among various procedures.

(b) Optional alloying element

Because of the generally low tempering temperatures, these die steels are employed primarily in hammer operations where the contact times, during which heat transfer to the dies can occur, are short. Alternatively, they can be used in presses as die blocks with heat-resistant inserts made from the hot-work die steels (H grades). An exception to this general trend among the low-alloy tool steels is alloy 6F4 (see Table 2). Its large nickel and molybdenum contents impart high hardness and hardenability. Furthermore, it is generally underaged. Because of this, when it is used in presses or upsetters, heat transfer gives rise to age hardening and thus increased resistance to abrasive wear.

The origin of the "ASM" designations for the proprietary steels listed in Table 2 dates back to the 1948 edition of Metals Handbook. ASM International does not issue standards of any kind. However, because these steels were never given designations by AISI, SAE, or the Unified Numbering System (UNS), they are still often referred to by their ASM designations. In the 1948 Handbook, tool steels were grouped into six broad categories. The steels under discussion here were grouped under category VI (6), "Miscellaneous Tool Steels." The letters of the designation referred to the principal alloying elements. Thus, 6G is a chromium-molybdenum steel, while the 6F steels are nickel-chromium-molybdenum compositions. The difference between steels 6F2 through 6F7 is in the amounts of these principal alloying elements (see Table 2). The 6H grades in Table 2 are a continuation of those used in the 1948 Metals Handbook and are similar to the chromium hot-work tool steels described above.

Cold-Work Steels

Cold-work tool steels, because they do not have the alloy content necessary to make them resistant to softening at elevated temperature, are restricted in application to those uses that do not involve prolonged or repeated heating above 205 to 260 °C (400 to 500 °F). There are three categories of cold-work steels; air-hardening steels (group A); high-carbon, high-chromium steels (group D); and oil-hardening steels (group O).

Air-hardening, medium-alloy, cold-work steels (group A) contain enough alloying elements to enable them to achieve full hardness in sections up to about 100 mm (4 in.) in diameter upon air cooling from the austenitizing temperature. (Type A6 through hardens in sections as large as a cube 175 mm, or 7 in., on a side.) Because they are air hardening, group A tool steels exhibit minimum distortion and the highest safety (least tendency to crack) in hardening. Manganese, chromium, and molybdenum are the principal alloying elements used to provide this deep hardening. Types A2, A3, A7, A8, and A9 contain a high percentage of chromium (5%), which provides moderate resistance to softening at elevated temperatures. (See curve 3 in Fig. 1 for a plot of hardness versus tempering temperature for type A2.)

Types A4, A6, and A10 are lower in chromium content (1%) and higher in manganese content (2%). They can be hardened from temperatures about 110 °C (200 °F) lower than those required for the high-chromium types, further reducing distortion and undesirable surface reactions during heat treatment.

To improve toughness, silicon is added to type A8, and both silicon and nickel are added to types A9 and A10. Because of the high carbon and silicon contents of type A10, graphite is formed in the microstructure. As a result, A10 has much better machinability in the annealed condition, and somewhat better resistance to galling and seizing in the fully hardened condition, than other group A tool steels.

Typical applications for group A tool steels include shear knives, punches, blanking and trimming dies, forming dies, and coining dies. The inherent dimensional stability of these steels makes them suitable for gages and precision measuring tools. In addition, the extreme abrasion resistance of type A7 makes it suitable for brick molds, ceramic molds, and other highly abrasive applications.

The complex chromium or chromium-vanadium carbides in group A tool steels enhance the wear resistance provided by the martensitic matrix. Therefore, these steels perform well under abrasive conditions at less than full hardness. Although cooling is still air is adequate for producing full hardness in most tools, massive sections should be hardened by cooling in an air blast or by interrupted quenching in hot oil.

High-carbon, high-chromium, cold-work steels (group D) contain 1.50 to 2.35% C and 12% Cr. With the exception of type D3, they also contain 1% Mo. All group D tool steels except type D3 are air hardening and attain full hardness when cooled in still air. Type D3 is almost always quenched in oil (small parts can be austenitized in vacuum and then gas quenched). Therefore, tools made of D3 are more susceptible to distortion and are more likely to crack during hardening.

Group D steels have high resistance to softening at elevated temperatures. These steels also exhibit excellent resistance to wear, especially type D7, which has the highest carbon and vanadium contents. All group D steels, particularly the higher-carbon types D3, D4, and D7, contain massive amounts of carbides, which make them susceptible to edge brittleness.

Typical applications of group D steels include long-run dies for blanking, forming, thread rolling, and deep drawing; dies for cutting laminations; brick molds; gages; burnishing tools; rolls; and shear and slitter knives.

Oil-hardening cold-work steels (group O) have high carbon contents, plus enough other alloying elements that small to moderate sections can attain full hardness when quenched in oil from the austenitizing temperature. Group O tool steels vary in type of alloy, as well as in alloy content, even though they are similar in general characteristics and are used for similar applications. Type O1 contains manganese, chromium, and tungsten. Type O2 is alloyed primarily with manganese. Type O6 contains silicon, manganese, and molybdenum. It has a high total carbon content that includes free carbon, as well as sufficient combined carbon to enable the steel to achieve maximum as-quenched hardness. Type O7 contains manganese and chromium and has a tungsten content higher than that of type O1.

The most important service-related property of group O steels is high resistance to wear at normal temperatures, a result of high carbon content. On the other hand, group O steels have a low resistance to softening at elevated temperatures.

The ability of group O steels to harden fully upon relatively slow quenching yields lower distortion and greater safety (less tendency to crack) in hardening than is characteristic of the water-hardening tool steels. Tools made from these steels can be successfully repaired or renovated by welding if proper procedures are followed. In addition, graphite in the microstructure of type O6 greatly improves the machinability of annealed stock and helps reduce galling and seizing of fully hardened steel.

Group O steels are used extensively in dies and punches for blanking, trimming, drawing, flanging, and forming. Surface hardnesses of 56 to 62 HRC, obtained through oil quenching followed by tempering at 175 to 315 °C (350 to 600 °F), provide a suitable combination of mechanical properties for most dies made from type O1, O2, or O6. Type O7 has lower hardenability but better general wear resistance than any other group O tool steel, and it is more often used for tools requiring keen cutting edges. Oil-hardening tool steels are also used for machinery components (e.g., cams, bushings, and guides) and for gages, where good dimensional stability and wear resistance properties are needed.

The hardenability of group O steels can be measured effectively by the Jominy end-quench test. Hardenability bands for group O steels are shown in Fig. 2.

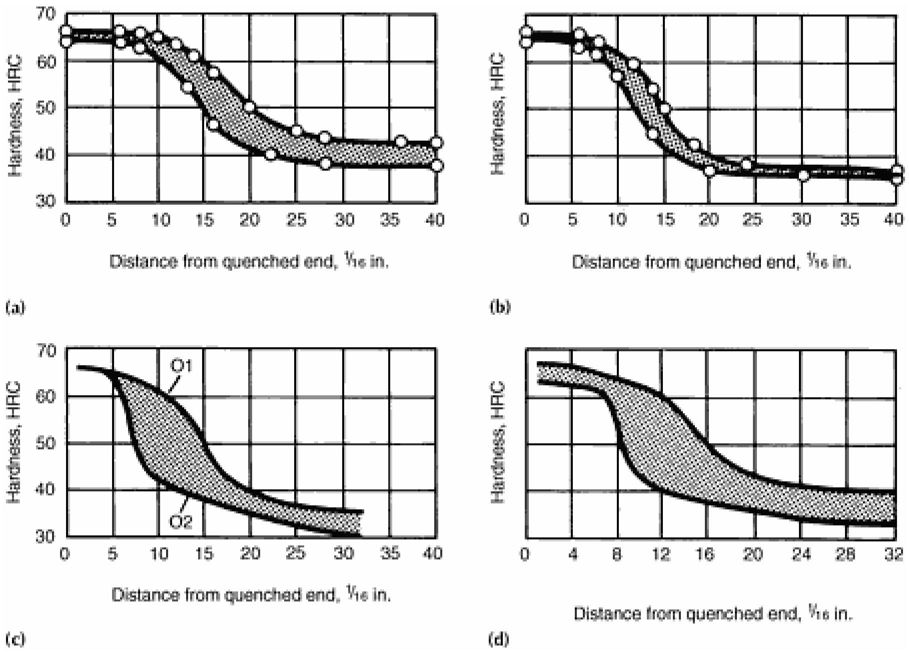


Fig. 2 End-quench hardenability bands for group O steels. (a) O1, source A. (b) O2, source A. (c) O1 and O2, source B. (d) 06. Hardenability bands from source B represent the data from five heats each for O1 and O2 tool steels. Data from source A were determined only on the basis of average hardness, not as hardenability bands. Data for O6 is for a spheroidized prior structure. Steels O1 and O6 were quenched from 815 °C (1500 °F); O2, from 790 °C (1450 °F).

At normal hardening temperatures, group O steels retain greater amounts of undissolved carbides and thus do not harden as deeply as do steels that are lower in carbon but similar in alloy content. On the other hand, group O steels attain higher surface hardness. Raising the hardening temperature increases grain size, increases solution of alloying elements, and dissolves more of the excess carbide, thereby increasing hardenability. However, raising the hardening temperature can have an adverse effect on certain mechanical properties, most notably ductility toughness, and also can increase the likelihood of cracking during hardening.

Shock-Resisting Steels

The principal alloying elements in shock-resisting steels, also called group S steels, are manganese, silicon, chromium, tungsten, and molybdenum, in various combinations. Carbon content is about 0.50% for all group S steels, which produces a combination of high strength, high toughness, and low to medium wear resistance. Group S steels are used primarily for chisels, rivet sets, punches, driver bits, and other applications requiring high toughness and resistance to shock loading. Types S1 and S7 are also used for hot punching and shearing, which require some heat resistance.

Group S steels vary in hardenability from shallow hardening (S2) to deep hardening (S7). In these steels of intermediate alloy content, hardenability is controlled to a greater extent by composition than by the incidental effects of grain size and melting practice, which are so important for group W steels. Group S steels require relatively high austenitizing temperatures to achieve optimal hardness; consequently, undissolved carbides are not a factor in the control of hardenability. Type S2 is normally water quenched; types S1, S5, and S6 are oil quenched; and type S7 is normally cooled in air, except that large sections are oil quenched.

Group S steels exhibit excellent toughness at high strength levels, so they are often considered for nontooling or structural applications.

Low-Alloy Special-Purpose Steels

Low-alloy special-purpose steels, also called group L steels, contain small amounts of chromium, vanadium, nickel, and molybdenum. At one time, seven steels were listed in this group, but because of falling demand, only types L2 and L6 remain. Type L2 is available in several carbon contents, from 0.50 to 1.10%. Its principal alloying elements are chromium and vanadium, which make it an oil-hardening steel of fine grain size. Type L6 contains small amounts of chromium and molybdenum, as well as 1.50% Ni for increased toughness.

Although both L2 and L6 are considered oil-hardening steels, large sections of L2 are often quenched in water. A type L2 steel containing 0.50% C is capable of attaining about 57 HRC as oil quenched, but it will not through harden in sections of more than about 13 mm (0.5 in.) thickness. Type L6, which contains 0.70% C, has an as-quenched hardness of about 64 HRC. It can maintain a hardness above 60 HRC through sections of 75 mm (3 in.) thickness.

Group L steels are generally used for machine parts, such as arbors, cams, chucks, and collets, and for other special applications requiring good strength and toughness.

Mold Steels

Mold steels, also called group P steels, contain chromium and nickel as principal alloying elements. Types P2 and P6 are carburizing steels produced to tool steel quality standards. They have very low hardness and low resistance to work hardening in the annealed condition. These factors make it possible to produce a mold impression by cold hubbing (hubbing is a technique for forming a mold cavity by forcing a hardness steel master hub, an exact replica of the article to be formed, into a softer die blank). After the impression is formed, the mold is carburized, hardened, and tempered to a surface hardness of about 58 HRC. Types P4 and P6 are deep hardening; with type P4, full hardness in the carburized case can be achieved by cooling in air.

Types P20 and P21 normally are supplied heat treated to 30 to 60 HRC, a condition in which they can be machined readily into large, intricate dies and molds. Because these steels are prehardened, no subsequent high-temperature heat treatment is required, and distortion and size changes are avoided. However, when used for plastic molds, type P20 is sometimes carburized and hardened after the impression has been machined. Type P21 is an aluminum-containing precipitation-hardening steel that is supplied prehardened to 32 to 36 HRC. This steel is preferred for critical-finish molds because of its excellent polishability.

All group P steels have low resistance to softening at elevated temperatures, with the exception of P4 and P21, which have medium resistance. Group P steels are used almost exclusively in low-temperature die casting dies and in molds for the injection or compression molding of plastics. Plastic molds often require massive steel blocks up to 762 mm (30 in.) thick and weighing as much as 9 metric tonnes (10 tons). Because these large die blocks must meet stringent requirements for soundness, cleanliness, and hardenability, electric furnace melting, vacuum degassing, and special deoxidation treatments have become standard practice in the production of group P tool steels. In addition, ingot casting and forging practices have been refined so that a high degree of homogeneity can be achieved.

Water-Hardening Steels

Water-hardening steels, also called group W steels, contain carbon as the principal alloying element. Small amounts of chromium are added to most of the group W steels to increase hardenability and wear resistance, and small amounts of vanadium are added to maintain fine grain size and thus enhance toughness. Group W tool steels are made with various nominal carbon contents (~0.60 to 1.40%); the most popular grades contain approximately 1.00% C.

Group W tool steels are very shallow hardening and consequently develop a fully hardened zone that is relatively thin, even when quenched drastically. Sections more than about 13 mm ($\frac{1}{2}$ in.) thick generally have a hard case over a strong, tough, and resilient core.

Group W steels have low resistance to softening at elevated temperatures. They are suitable for cold heading, striking, coining, and embossing tools; woodworking tools; hard metal-cutting tools, such as taps and reamers; wear-resistant machine tool components; and cutlery.

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Properties of Tool Steels

The basic properties of tool steels that determine their performance in service are hardness; resistance to wear, deformation, and breakage; toughness; and, in many instances, resistance to softening at elevated temperatures. It is difficult to obtain reliable correlations between the properties of tool steels as measured by laboratory tests and the performance of these steels in service or in fabrication, so these properties are often presented as general comparisons rather than as specific data. Property and fabrication characteristic comparisons are given in Table 3 and in Fig. 3 and 4.

Table 3 Processing and service characteristics of tool steels

AISI designation	Resistance to decarburization	Hardening and tempering				Fabrication and service			
		Hardening response	**Amount of distortion[(a)]**	**Resistance to cracking**	**Approximate hardness[(b)], HRC**	**Machinability**	**Toughness**	**Resistance to softening**	**Resistance to wear**
Molybdenum high-speed steels									
M1	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Very high	Very high
M2	Medium	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Very high	Very high
M3 (class 1 and class 2)	Medium	Deep	A or S, low; O, medium	Medium	61-66	Medium	Low	Very high	Very high
M4	Medium	Deep	A or S, low; O, medium	Medium	61-66	Low to medium	Low	Very high	Highest
M7	Low	Deep	A or S, low; O, medium	Medium	61-66	Medium	Low	Very high	Very high
M10	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Very high	Very high
M30	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	Very high
M33	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	Very high

M34	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	Very high
M35	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	Very high
M36	Low	Deep	A or S, low; O, medium	Medium	60-65	Medium	Low	Highest	Very high
M41	Low	Deep	A or S, low; O, medium	Medium	65-70	Medium	Low	Highest	Very high
M42	Low	Deep	A or S, low; O, medium	Medium	65-70	Medium	Low	Highest	Very high
M43	Low	Deep	A or S, low; O, medium	Medium	65-70	Medium	Low	Highest	Very high
M44	Low	Deep	A or S, low; O, medium	Medium	62-70	Medium	Low	Highest	Very high
M46	Low	Deep	A or S, low; O, medium	Medium	67-69	Medium	Low	Highest	Very high
M47	Low	Deep	A or S, low; O, medium	Medium	65-70	Medium	Low	Highest	Very high
M48	Low	Deep	A or S, low; O, medium	Medium	65-70	Low	Low	Highest	Highest
M62	Low	Deep	A or S, low; O, medium	Medium	62-68	Medium	Low	Highest	Very high

Tungsten high-speed steels									
T1	High	Deep	A or S, low; O, medium	High	60-65	Medium	Low	Very high	Very high
T2	High	Deep	A or S, low; O, Medium	High	61-66	Medium	Low	Very high	Very high
T4	Medium	Deep	A or S, low; O, Medium	Medium	62-66	Medium	Low	Highest	Very high
T5	Low	Deep	A or S, low; O, Medium	Medium	60-65	Medium	Low	Highest	Very high
T6	Low	Deep	A or S, low; O, Medium	Medium	60-65	Low to medium	Low	Highest	Very high
T8	Medium	Deep	A or S, low; O, Medium	Medium	60-65	Medium	Low	Highest	Very high
T15	Medium	Deep	A or S, low; O, Medium	Medium	63-68	Low to medium	Low	Highest	Highest
Intermediate high-speed steels									
M50	Low	Deep	A or S, low; O, Medium	Medium	58-63	Medium	Low	High	High
M52	Low	Deep	A or S, low; O, medium	Medium	58-64	Medium	Low	High	High
Chromium hot-work steels									

H10	Medium	Deep	Very low	Highest	39-56	Medium to high	High	High	Medium
H11	Medium	Deep	Very low	Highest	38-54	Medium to high	Very high	High	Medium
H12	Medium	Deep	Very low	Highest	38-55	Medium to high	Very high	High	Medium
H13	Medium	Deep	Very low	Highest	38-53	Medium to high	Very high	High	Medium
H14	Medium	Deep	Low	Highest	40-47	Medium	High	High	Medium
H19	Medium	Deep	A, low; O, medium	High	40-57	Medium	High	High	Medium to high
Tungsten hot-work steels									
H21	Medium	Deep	A, low; O, medium	High	36-54	Medium	High	High	Medium to high
H22	Medium	Deep	A, low; O, medium	High	39-52	Medium	High	High	Medium to high
H23	Medium	Deep	Medium	High	34-47	Medium	Medium	Very high	Medium to high
H24	Medium	Deep	A, low; O, medium	High	45-55	Medium	Medium	Very high	High
H25	Medium	Deep	A, low; O, medium	High	35-44	Medium	High	Very high	Medium
H26	Medium	Deep	A or S, low; O, medium	High	43-58	Medium	Medium	Very high	High

Molybdenum hot-work steels									
H42	Medium	Deep	A or S, low; O, medium	Medium	50-60	Medium	Medium	Very high	High
Air-hardening, medium-alloy, cold-work steels									
A2	Medium	Deep	Lowest	Highest	57-62	Medium	Medium	High	High
A3	Medium	Deep	Lowest	Highest	57-65	Medium	Medium	High	Very high
A4	Medium to high	Deep	Lowest	Highest	54-62	Low to medium	Medium	Medium	Medium to high
A6	Medium to high	Deep	Lowest	Highest	54-60	Low to medium	Medium	Medium	Medium to high
A7	Medium	Deep	Lowest	Highest	57-67	Low	Low	High	Highest
A8	Medium	Deep	Lowest	Highest	50-60	Medium	High	High	Medium to high
A9	Medium	Deep	Lowest	Highest	35-56	Medium	High	High	Medium to high
A10	Medium to high	Deep	Lowest	Highest	55-62	Medium to high	Medium	Medium	High
High-carbon, high-chromium, cold-work steels									
D2	Medium	Deep	Lowest	Highest	54-61	Low	Low	High	High to very high

D3	Medium	Deep	Very Low	High	54-61	Low	Low	High	Very high
D4	Medium	Deep	Lowest	Highest	54-61	Low	Low	High	Very high
D5	Medium	Deep	Lowest	Highest	54-61	Low	Low	High	High to very high
D7	Medium	Deep	Lowest	Highest	58-65	Low	Low	High	Highest
Oil-hardening cold-work steels									
O1	High	Medium	Very low	Very high	57-62	High	Medium	Low	Medium
O2	High	Medium	Very low	Very high	57-62	High	Medium	Low	Medium
O6	High	Medium	Very low	Very high	58-63	Highest	Medium	Low	Medium
07	High	Medium	O, very low; W, high	W, low; O, very high	58-64	High	Medium	Low	Medium
Shock-resisting steels									
S1	Medium	Medium	Medium	High	40-58	Medium	Very high	Medium	Low to medium
S2	Low	Medium	High	Low	50-60	Medium to high	Highest	Low	Low to medium
S5	Low	Medium	Medium	High	50-60	Medium to high	Highest	Low	Low to medium
S6	Low	Medium	Medium	High	54-56	Medium	Very high	Low	Low to medium

S7	Medium	Deep	A, lowest; O, low	O, high; A, highest	45-57	Medium	Very high	High	Low to medium
Low-alloy special-purpose steels									
L2	High	Medium	O, medium; W, low	O, medium; W, high	45-63	High	Very high(c)	Low	Low to medium
L6	High	Medium	Low	High	45-62	Medium	Very high	Low	Medium
Low-carbon mold steels									
P2	High	Medium	Low	High	58-64(c)	Medium to high	High	Low	Medium
P3	High	Medium	Low	High	54-64(c)	Medium	High	Low	Medium
P4	High	High	Very low	High	58-64(c)	Low to medium	High	Medium	High
P5	High	. . .	O, low; W, high	High	58-64(c)	Medium	High	Low	Medium
P6	High	. . .	A, very low; O, low	High	58-61(c)	Medium	High	Low	Medium
P20	High	Medium	Low	High	28-37	Medium to high	High	Low	Low to medium
P21	High	Deep	Lowest	Highest	30-40(d)	Medium	Medium	Medium	Medium
Water-hardening steels									
W1	Highest	Shallow	High	Medium	50-64	Highest	High(e)	Low	Low to medium

W2	Highest	Shallow	High	Medium	50-64	Highest	High[e]	Low	Low to medium
W3	Highest	Shallow	High	Medium	50-64	Highest	High[e]	Low	Low to medium

Source: Ref 1

(a) A, air cool; B, brine quench; O, oil quench; S, salt bath quench; W, water quench.

(b) After tempering in temperature range normally recommended for this steel.

(c) Carburized case hardness.

(d) After aging at 510 to 550 °C (950 or 1025 °F).

(e) Toughness decreases with increasing carbon content and depth of hardening.

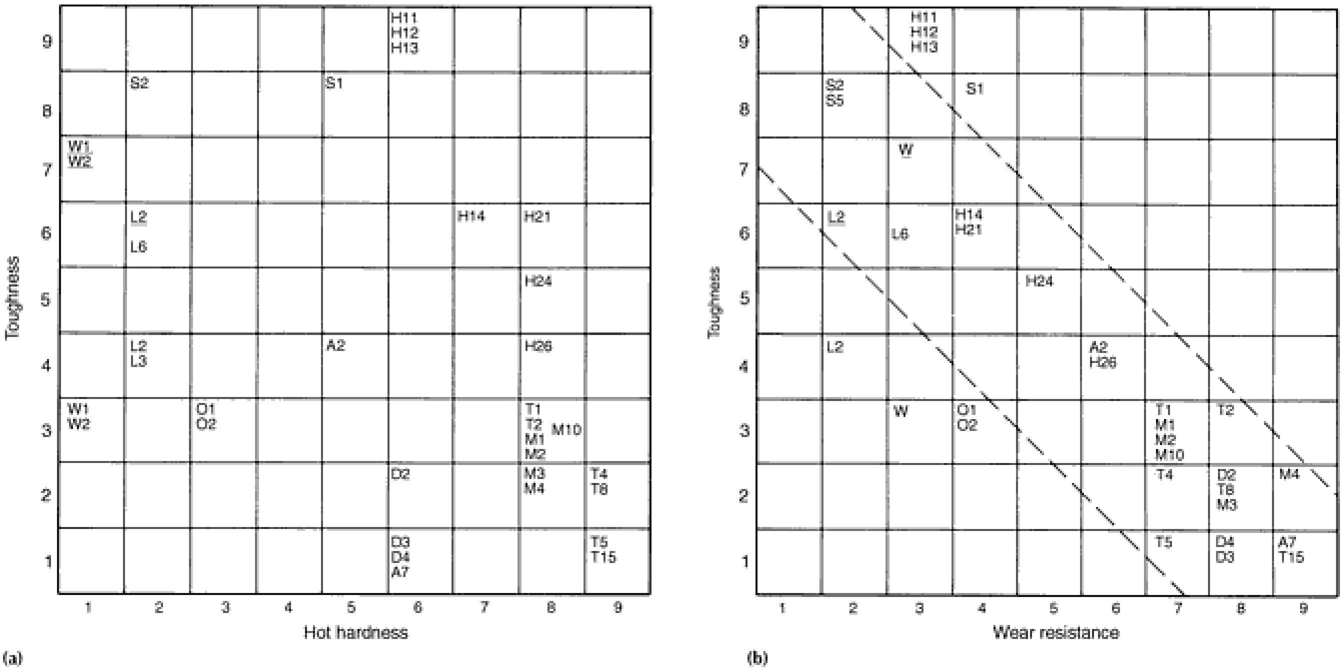

Fig. 3 Plots of toughness against (a) hot hardness and (b) wear resistance for tool steels. Types underlined indicate shallow-hardened tool steels. The area between the dashed lines in (b) represents average values.

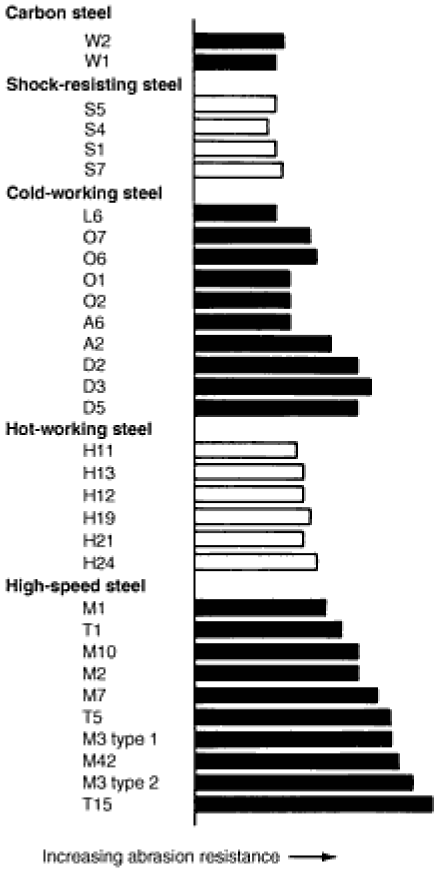

Fig. 4 Relative abrasion resistance of tool steels

Hardness is the most commonly stipulated requirement of a tool steel and is used as an acceptance check of a heat-treated tool. Often the property or fabrication characteristics of tool steels can be measured by, or inferred from, the measurements of hardness. For example, high hardness improves strength and wear resistance but lowers toughness. As indicated in Table 3, the hardness of tool steel is most commonly measured and reported on the Rockwell C scale (HRC).

Hot hardness, the retention of high hardness at elevated temperature, is an important property for tool steels used for machining and hot metalworking applications. The ability of a tool steel to resist thermal softening is related to its ability to develop secondary hardening and to the amount of special phases, such as excess alloy carbides, in the microstructure. Useful information on the ability of tool steels to resist thermal softening at elevated temperatures can be obtained from tempering curves such as those shown in Fig. 1. Hardness testing at elevated temperatures (see Table 4) also can provide useful information.

Table 4 Hot hardness of selected high-speed tool steels and die steels

AISI designation	Hardness, HRC				
	Room temperature	**Hot hardness[(a)]**			
		315 °C (600 °F)	**425 °C (800 °F)**	**540 °C (1000 °F)**	**650 °C (1200 °F)**
High-speed tool steels					
M1	65	61	58	54	32
M2	65	62	59	55	36
M3, class 1	65	63	60	56	36
M3, class 2	65	63	60	56	36
M4	66	63	60	56	37
M7	65	61	58	54	35
M10	65	60	57	52	33
M30	65	63	58	55	35
M33	65	64	60	57	40
M36	65	64	60	57	40
M42	68	66	65	62	44
M50	64	59	57	52	. . .

M52	64	60	57	53	. . .
T1	65	61	57	53	33
T4	65	61	59	55	38
T5	66	62	60	56	40
T15	68	64	61	57	42
Cold-work die steels					
A2	60	52	46	35	. . .
A8	58	55	52	45	. . .
D2	60	53	47	38	. . .
D4	62	52	46	37	. . .
Hot-work die steels					
A8	58	55	52	45	. . .
H11	54	49	47	42	22
H12	54	49	47	42	22
H13	55	49	47	42	22
H19	54	51	47	42	31
H21	54	52	49	45	29
H23	41	32	30	28	25
H26	58	54	50	46	31

Source: Ref 2

(a) Small-diameter bars tested according to the recommended heat treatment.

Figure 5 shows hot hardnesses of five hot-work die steels at various temperatures. All of these steels were heat treated to about the same initial hardness. Hardness measurements were made after holding the specimens at testing temperature for 30 min. Except for H12, all the die steels considered have about the same hot hardness at temperatures below about 315 °C (600 °F). The differences in hot hardness show up only at temperatures above 480 °C (900 °F).

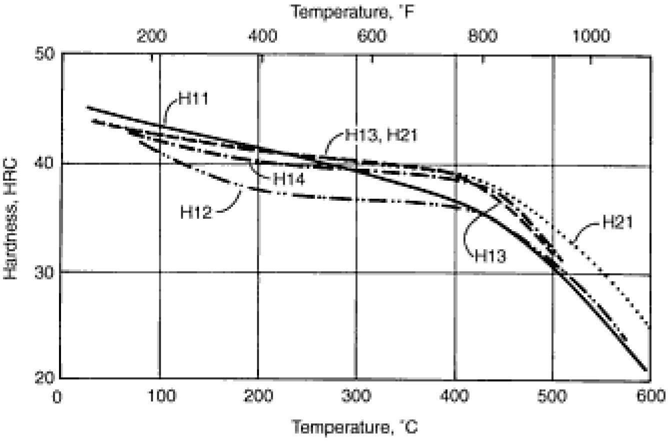

Fig. 5 Hot hardnesses of AISI hot-work tool steels. Measurements were made after holding at the test temperature for 30 min.

Figure 6 shows the resistance of some hot-work die steels to softening at elevated temperatures after 10 h of exposure. All of these steels have about the same initial hardness after heat treatment. For the die steels shown, there is not much variation in resistance to softening at temperatures below 540 °C (1000 °F). However, for longer periods of exposure at higher temperatures, high-alloy hot-work steels, such as H19, H21, and H10 modified, retain hardness better than do medium-alloy steels, such as H11.

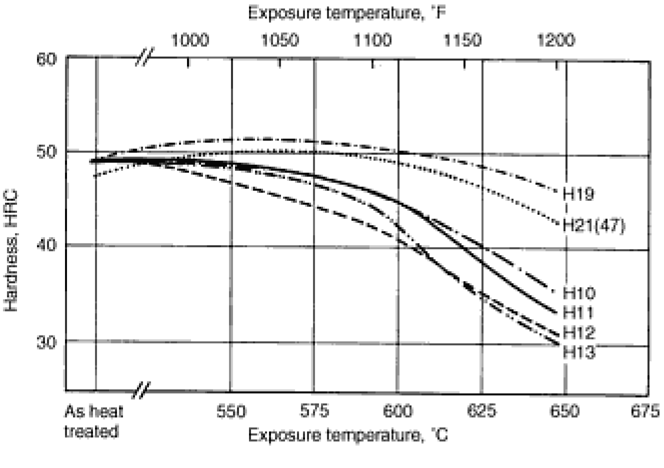

Fig. 6 Resistance of AISI hot-work tool steels to softening during 10 h elevated-temperature exposure as measured by room-temperature hardness. Unless otherwise specified by values in parentheses, initial hardness of all specimens was 49 HRC.

Resistance to Abrasive Wear. The high wear resistance of heat-treated tool steels is attributable to the hardness of the matrix phase, chiefly martensite, and the amount and type of carbides remaining undissolved in the matrix. The amount and type of carbides present depend on the bulk carbon content and the quantity of carbide-forming elements (chromium, molybdenum, vanadium, and tungsten, for example) in the grade. Cementite is present in the carbon and low-alloy grades; more complex carbide types are found in the highly alloyed grades (Table 5). The hardness of carbides varies with their composition, from approximately 800 HV for cementite to approximately 1400 HV when other elements, such as chromium, are substituted for a portion of the iron.

Table 5 Characteristics of alloy carbides found in tool steels

Type of carbide	Lattice type	Remarks
M_3C	Orthorhombic	This is a carbide of the cementite (Fe_3C) type, maybe Fe, Mn, Cr with a little W, Mo, V.
M_7C_3	Hexagonal	Mostly found in Cr alloy steels. Resistance to dissolution at higher temperatures. Hard and abrasion resistant. Found as a product of tempering high-speed steels.
$M_{23}C_6$	Face-centered cubic	Present in high-Cr steels and all high-speed steels. The Cr can be replaced with Fe to yield carbides with W and Mo.
M_6C	Face-centered cubic	Is a W- or Mo-rich carbide. May contain moderate amounts of Cr, V, Co. Present in all high-speed steels. Extremely abrasion resistant.
M_2C	Hexagonal	W- or Mo-rich carbide of the W_2C type. Appears after temper. Can dissolve a considerable amount of Cr.
MC	Face-centered cubic	V-rich carbide. Resists dissolution. Small amount that does dissolve reprecipitates on secondary hardening.

Source: Ref 3

Figure 7 is a graphical comparison of the hardness of various alloy carbides relative to the hardness of martensite and cementite (Fe_3C). As shown, the precipitated metal carbides such as MC and M_2C attain very high hardness, and they contribute significant wear resistance to tool steels that are alloyed to contain large volume fractions of carbides. For example, high-speed tool steels may contain as much as 30 vol% of carbides, consisting of a mixture of MC, $M_{23}C_6$, and M_6C.

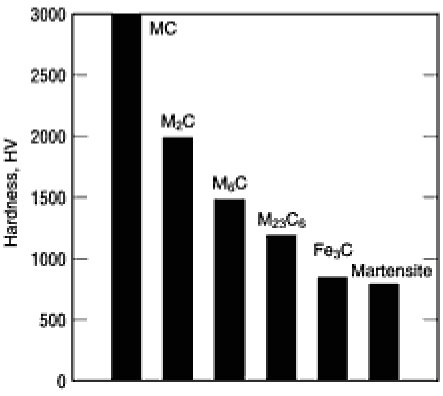

Fig. 7 Relative hardness of alloy carbides, cementite, and martensite in high-speed steels. Source: Ref 4

A detailed study of the dry abrasive wear of tool steels was conducted by Budinski (Ref 5). His assessment of the data showed very good correlation with a structural parameter, A, which equals the primary carbide size, multiplied by the volume fraction of carbides, multiplied by carbide hardness. The data are shown in Fig. 8. The implication of this finding is that the most abrasion-resistant tool steel has a large volume fraction of large, hard carbides.

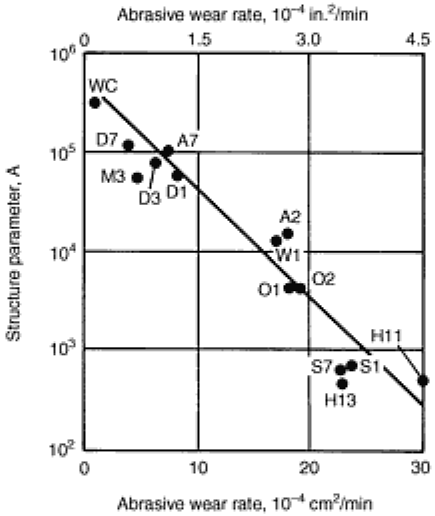

Fig. 8 Abrasion resistance of tool steels versus a structure parameter, A, that equals the primary carbide size, multiplied by the volume fracture of carbides, multiplied by carbide hardness. Source: Ref 5

Care must be used in committing these results to steelmaking practice. Most wear is metal to metal; therefore, abrasion is not the only mechanism involved. In addition, if large carbides are torn from the tool steel matrix, they will enhance tool steel wear by adding abrasive carbide particles to the wear debris. This effect can also occur if tool steels are overtempered.

Resistance to Adhesive Wear. Adhesive wear between tool steel and workpiece can result when direct contact occurs because of lubricant breakdown, high pressures, or process design. This type of wear is due to the cold welding of microscopic asperities between the tool and the workpiece. The environment also has an effect. Generally, adhesive wear becomes more severe as oxygen content decreases (for example, sliding in a vacuum), because no oxide layer can form.

Metallurgical factors that decrease the adhesive wear of tool steels include higher tool steel hardness at temperature (hot hardness), the built-in lubricity of graphite tool steels (types O6 and A10), small grain size (Ref 6), a large volume fraction of primary carbides (Ref 7), and small primary carbide size (Ref 6).

Resistance to Deformation. For all practical purposes, the resistance to elastic deformation (modulus of elasticity) of all tool steels in all conditions is about 210 GPa (30×10^6 psi) at room temperature. This decreases uniformly to about 185 GPa (27×10^6 psi) at 260 °C (500 °F) and to about 150 GPa (22×10^6 psi) at 540 °C (1000 °F).

Toughness. The amount of energy absorbed when a notched bar of fully hardened tool steel (except for certain grades) is broken in impact (Charpy V-notch test) is so small that it is very difficult to measure the differences in toughness that may make it possible to predict service performance. In addition, many tool steels have Charpy V-notch impact values of only a few joules. There is an error of ±1.5 J associated with conventional Charpy V-notch testing, so some consider this mode of testing to be questionable. Charpy values for low-toughness steels should be measured on low-blow machines for reproducible results. Unnotched Izod values are the most commonly reported laboratory test values for fracture resistance and toughness of tool steels. However, excessive deformation of supporting fixtures makes it very difficult to obtain reproducible results. Torsion impact testing yields useful, reproducible data on the effects of variations on the composition and heat treatment of tool steels; however, it is difficult to correlate the results of such testing with service experience. Fatigue tests have been useful for research, but only in some instances have the results correlated well with field experience. Plane-strain fracture toughness tests that yield K_{Ic} values are also being used increasingly often. However, for most tool steel applications, the tooling is subject to a high strain rate, and fracture toughness may not be critical. (The normal failure mode for a tool steel in a typical application such as a highly stressed blanking die would be a catastrophic failure, which would be better simulated by high strain rate testing including Charpy or Izod impact tests.) Results of Charpy, Izod, and fracture toughness tests are compared in Fig. 9.

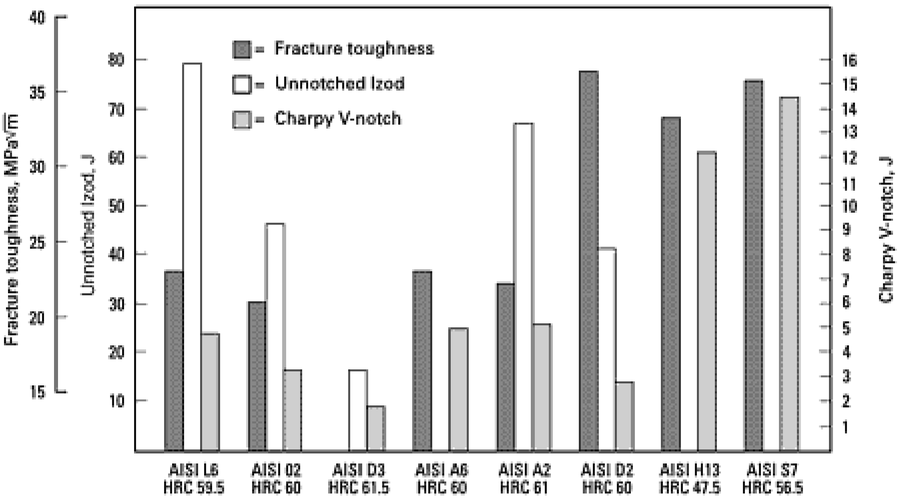

Fig. 9 Comparison of fracture toughness (K_{IC}), longitudinal unnotched Izod, and longitudinal Charpy V-notch impact results for 89 mm (3.5 in.) square tool steel bars at working hardness. Source: Ref 8

In general, the ability of tool steels to withstand the rapid application of high loads without breaking increases with decreasing hardness. With hardness held constant, wide differences can be observed among tool steels of different compositions, or among steels of the same nominal composition made by different melting practices or heat treated according to different schedules.

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Effects of Surface Treatments on Properties

Most surface treatments are employed to increase surface hardness and/or wear resistance, minimize adhesion (reduce friction), or improve the corrosion resistance of the tool steel base.

Carburizing. The processes of case hardening and carburizing are of limited use in tool steel applications, because of the relatively high carbon contents of the tool steels. Carburizing can be accomplished in many ways and essentially consists of heating the final machined tool into the austenite region in the presence of carbonaceous solids, liquids, or gases.

Low-carbon plastic mold steels (P type) are often carburized after hubbing or machining of the cavity in the mold. In this application, the tool steel is intentionally lean in carbon content to improve hubbing or machining and must be carburized in order to have sufficient surface hardness for the end use.

Nitriding is a frequently used surface treatment that increases surface hardness, adds to the corrosion resistance of the tool, and reduces friction. Basically, the process involves heating the finished tool in the presence of a nitrogen-containing liquid or gas and allowing nitrogen to diffuse into the tool. Gas nitriding is usually accomplished at a lower temperature (about 527 °C, or 980 °F) and longer time (10 to 90 h) than liquid nitriding, which occurs at temperatures ranging from 538 to 552 °C (1000 to 1025 °F) for 2 to 4 h. A nitrided depth that ranges from 13 to 76 μm (0.005 to 0.003 in.) is desired.

Because of decreased wear and die pickup, cold-extrusion punches experience a two- to threefold improvement in life. Nitriding is often used whenever mold wash is a problem in the die casting of zinc or aluminum alloys. Galling of sheet metal working dies can be alleviated by nitriding these dies before use.

Steels that will be nitrided should contain one or more of the nitride-forming elements (chromium, vanadium, or aluminum) in order to prevent the easy spalling and chipping that results when iron nitride is formed. Commonly nitrided tool steels include H11, H12, H13, A2, O2, and the high-speed tool steels.

Ion or plasma nitriding has many of the same characteristics of liquid or gas nitriding. This process relies on nitrogen gas being ionized by glow discharge conditions between the tool (cathode) and the furnace wall or shield (anode). The primary advantages are the reductions in time and temperature, which save money and reduce the distortion and softening of prehardened tools. Usually, treatment times vary between 0.5 and 36 h.

In the Toyota diffusion (TD) process, metal dies to be treated are degreased, immersed in a carbide salt bath for a specific time period, quenched for core hardening, tempered, and washed in hot water for the removal of any residual salt. The borax salt bath contains compounds (usually ferroalloys) with carbide-forming elements such as vanadium, niobium, and chromium. The bath temperature is selected to conform to the hardening (austenitizing) temperature of the die steel. For example, the borax bath temperature should be between 1000 and 1050 °C (1830 and 1920 °F) for H13 die steel. Coating thicknesses range from 2 to 10 μm (0.0001 to 0.0004 in.).

Tool steels that contain 0.3% C or more may be TD processed. This includes most cold- and hot-work steels, high-speed steels, and some martensitic stainless steels. Coatings employed include vanadium carbide (VC) and niobium carbide (NbC) for applications requiring high surface hardness (3000 HV or higher) and resistance to wear, seizure, and corrosion, and chromium carbide (Cr_7C_3 and $Cr_{23}C_6$) for applications requiring light wear resistance and high resistance to oxidation.

Oxidation is a well-established process used for high-speed steel-cutting tools. Increases in tool life of up to 100% are mostly due to a decrease in friction, because of the hard oxide coating and the ability of the porous oxide to entrap lubricant and draw it to the tool/workpiece interface (Ref 9). Steam oxidation of a finished tool is accomplished either by exposure to steam at a temperature of about 566 °C (1050 °F) or by treating in liquid sodium hydroxide and sodium nitrate salts at approximately 140 °C (285 °F) for periods of time ranging from 5 to 20 min. These treatments result in a black oxidized layer that is less than 5 μm (0.0002 in.) thick and will not peel, chip, nor crack, even when the tool is bent or cut.

Boriding. In this process, boron atoms from a solid, liquid, gas, or plasma atmosphere surrounding the finished part are diffused into the surface creating a hard, wear-resistant iron boride layer. Metal-to-metal wear testing demonstrated a threefold improvement in wear resistance of borided O1 and O2 tool steels and over a twofold increase in A2 tool steel (Ref 10). Borided A2 tool steel showed twice the life of uncoated O2 tool steel in a deep-drawing operation in which low-carbon steel cups were manufactured (Ref 10). An H13 roller designed to flange milk cans was borided and produced three times as many cans before it wore out (Ref 11).

Boriding takes place at temperatures as low as 600 °C (1100 °F), but usual practice involves a period from 1 to 6 h at temperatures from 800 to 900 °C (1470 to 1650 °F) (Ref 10, 11). The resultant layer is between 13 and 130 μm (0.0005 and 0.005 in.) and tends to be dull because of the microroughness of the surface. The high process temperature requires that the boron treatment act as the austenitization step, or else the process must be followed by reaustenitization. This necessarily limits the process to applications where tolerances of about 25 μm (0.001 in.) can be tolerated.

Plating. The most commonly practiced tool steel plating process is hard chromium plating. Plating thickness varies between 2 and 13 μm (0.0001 and 0.0005 in.) and because it is very hard, it prolongs life by increasing abrasive wear resistance. More important than plating hardness is its very low friction coefficient, which effectively prevents adhesive wear.

However, hard chromium plating is not without problems. Tool steels may be hydrogen embrittled when plated, and the plating has a tendency to spall and flake. These wear debris can actually accelerate abrasive wear.

Electroless nickel plating has been used successfully as a replacement for chromium plating, both in routine production and for salvage plating operations on tool steel parts. Coating thicknesses for molds and dies range from 15 to 50 μm (0.0006 to 0.002 in.). Typical applications include zinc die-casting dies, glass molds, plastic injection molds, and plastic extrusion dies.

Plating by this method is accomplished by means of chemical reduction, so it does not depend on any galvanic coupling between dissimilar metals, and there is no electrolysis involved. Therefore, there is no danger of hydrogen embrittlement.

Chemical vapor deposition (CVD), a process conducted in a vacuum chamber, relies on a deposition from reacted gas onto the tool steel surface. Many different materials can be used as coatings. Chromium, Al_2O_3, TiC, CrC, Fe_4N, and TiN are commonly used, and other materials are being studied. This process utilizes high temperatures, usually above 800 °C (1472 °F), which means that tool steels must be tempered after the CVD coating is applied. The most popular wear-resistant coatings are TiC and TiN, which are used to coat high-speed, cold-work die and hot-work die tool steels. These coatings commonly range in thickness from 2.20 μm (0.0001 to 0.001 in.). Using CVD coating with TiC and TiN, the primary mechanism of wear reduction is the extremely high hardness, which leads to excellent abrasion resistance, although some decrease in friction coefficient can often be realized.

Tool steels that can be successfully CVD coated include the AISI A, S, D, H, M, and T steel types. The lower-alloyed S type and all of the W and O types are either very difficult or impossible to properly coat, because of their low austenitization temperatures.

Physical vapor deposition (PVD), which is also conducted in a vacuum chamber, can be accomplished in several different ways. The process relies on plasma-aided precipitation of either TiC or TiN onto tool steel at temperatures ranging from 200 to 550 °C (400 to 1025 °F) (Ref 12). This temperature range is much more suitable for the coating of high-speed tool steels than the temperature required for CVD.

Tool steel wear is reduced in about the same proportions (2 to 6 times less wear), whether the TiC or TiN is applied by CVD or PVD. TiN coatings on H13 pins reduced the friction coefficient in pin-on disk tests from 0.7 to less than 0.2 (Ref 13). Modified ASTM G65-10 abrasive wear testing of D3 steel showed that wear of the TiN-coated samples was between 4 and 23% of the uncoated samples, depending on their initial surface roughness (Ref 13). This result led Sundquist et al. to propose that increases in tool life that are due to TiN coating can only be expected when the surface roughness is less than the coating thickness (Ref 13).

Ion implantation is a process by which atoms of virtually any element can be injected into the near-surface region of any solid. The process involves forming a beam of charged ions of the desired element and then accelerating them at high energies toward the surface of the solid, which is held under high vacuum. The atoms penetrate into the solid to a depth of 0.25 to 25 nm (2.5 to 250 Å). This process differs from coating processes in that it does not produce a discrete coating; rather, it alters the chemical composition near the surface of the solid.

The number of applications involving the reduction of wear in stamping and punching tools probably exceeds all other uses if ion implantation for metals. The dominate cause of failure in high-speed tool steels used in metal stamping is adhesive wear. Ion implantation of nitrogen or titanium and carbon has provided the optimal treatment for such tools. For example, the life of punches and dies for manufacturing aluminum beverage cans has increased to 6 to 10 times that of untreated tooling. Similarly, punches for pressing powders into pellets have lasted twice as long after being treated. These applications range from forming pharmaceutical pills to more demanding service such as pressing ceramic pellets.

Ion implantation has also been used on a variety of low-temperature (to 200 °C, or 390 °F) cutting and slitting tools. Knife blades for cutting synthetic fibers have been implanted with titanium and carbon to improve wear resistance. Other applications include slitting blades for cutting rubber, hay baling cord cutters, plastic bandage cutter tools, corn-husking blades, paper slitters, and paper punches. Typical life improvements of 6 to 10 times have been reported for most of these applications (Ref 14). Other applications include ion implantation of injected molds for plastics and metal powders and extrusion and wire-drawing tools.

It should be noted that the ion implantation process is better suited to forming tools and dies than to cutting tools. This is attributable to the shallow implanted layer and the fact that a rise in temperature, such as may be expected in many cutting tools, causes diffusion of nitrogen into the specimen with the loss of the surface effect.

Micropeening. A proprietary surface treatment has been developed that uses controlled impaction of a small blasting media to develop rough texture and beneficial compressive stresses on the surface of dies and molds (Ref 15, 16, 17, 18). The rough texture increases the die lubricant retention characteristics, and the residual compressive stresses inhibit the initiation of fatigue microcracks due to the mechanical or thermal cycling of die surfaces during operation. This induced residual compressive strength has a subsurface penetration of 0.25 to 0.50 mm (0.010 to 0.020 in.) on dies that have not been nitrided and whose hardness is between 44 to 48 HRC. The impaction process also contributes a slight work hardening of the surface, which elevates the effective yield strength of the die as much as 25%.

Punch and die life increases of 6 to 10 times are claimed using this micropeening treatment. Drawing and forming dies have shown life improvements of 10 to 20 times in certain cases. Significant benefits can also be realized with cutting tools. In the field of die casting, micropeening has been used to increase the service life of new dies, close heat-checking cracks in used dies, and eliminates the deleterious effects of electrical discharge machining (EDM).

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Fabrication Characteristics

The properties that influence the ease of fabrication of tool steels include machinability; grindability; weldability; hardenability; and extent of distortion, safety (freedom from cracking), and tendency to decarburize during heat treatment.

Machinability of tool steels can be measured by the usual methods applied to constructional steels. Results are reported as percentages of the machinability of water-hardening tool steels (Table 6); 100% machinability in tool steels is equivalent to about 30% machinability in constructional steels, for which 100% machinability would be that of a free-machining constructional steel such as B1112. Improving the machinability of a tool steel by altering either the composition or the preliminary heat treatment can be very important if a large amount of machining is required to form the tool and a large number of tools are to be made.

Table 6 Approximate machinability ratings for annealed tool steels

Type	Machinability rating
O6	125
W1, W2, W5	100[(a)]
A10	90
P2, P3, P4, P5, P6	75-90
P20, P21	65-80
L2, L6	65-75
S1, S2, S5, S6, S7	60-70
H10, H11, H13, H14, H19	60-70[(b)]
O1, O2, O7	45-60
A2, A3, A4, A6, A8, A9	45-60
H21, H22, H24, H25, H26, H42	45-55[(b)]
T1	40-50
M2	40-50
T4	35-40
M3, class 1	35-40
D2, D3, D4, D5, D7, A7	30-40
T15	25-30
M15	25-30

(a) Equivalent to approximately 30% of the machinability of B1112.

(b) For hardness range 150 to 200 HB

Grindability. One measure of grindability is the ease with which the excess stock on heat-treated tool steel can be removed using standard grinding wheels. The grinding ratio (grindability index) is the volume of metal removed per volume of wheel wear. The higher the grindability index, the easier the metal is to grind (grinding ratios generally decrease as alloy and carbon contents increase). The index is valid only for specific sets of grinding conditions.

It should be noted that the grindability index does not indicate susceptibility to cracking during or after grinding, ability to produce the required surface (and subsurface) stress distribution, or ease of obtaining the required surface smoothness.

Weldability. The ability to construct, alter, or repair tools by welding without causing the material to crack may be an important factor in the selection of a tool material, especially if the tool is large. It is only rarely important in selecting materials for small tools. Weldability is largely a function of composition, but welding method and procedure also influence weld soundness. Generally, tool steels are more readily welded if they are deep hardening and are classified as having relatively high safety in hardening. In general, the lower-alloy tool steel grades have these characteristics.

Hardenability includes both the maximum hardness obtainable when the quenched steel is fully martensitic and the depth of hardening obtained by quenching in a specific manner. In this context, depth of hardening must be defined, generally as a specific value of hardness or a specific microstructural appearance. As a very general rule, maximum hardness of a tool steel increases with increasing carbon content; increasing the austenitic grain size and the amount of alloying elements reduces the cooling rate required to produce maximum hardness (increases the depth of hardening). The Jominy end-quench test, which is applied extensively to measure hardenability of construction steels, has limited application to tool steels. This test gives useful information only for oil-hardening grades. Air-hardening grades are so deep hardening that the standard Jominy test is not sufficient to evaluate hardenability.

An air-hardenability test has been developed that is based on the principles involved in the Jominy test, but which uses only still-air cooling and a 150 mm (6 in.) diameter end block to produce the very slow cooling rates of large sections. Such tests provide useful information for research but are of limited use for devising production heat treatments. By contrast, water-hardening grades of tool steel are so shallow hardening that the Jominy test is not sensitive enough. Special tests, such as the Shepherd penetration-fracture (P-F) test, are useful for research and for special applications of water-hardening tool steels.

In the Shepherd P-F test, a bar 19 mm ($\frac{3}{4}$ in.) in diameter, in the normalized condition, is brine quenched from 790 °C (1450 °F) and fractured. The case depth (penetration, P) is measured in 0.4 mm ($\frac{1}{64}$ in.) intervals, and the fracture grain size of the case (F) is determined by comparison with standard specimens. For example, a P-F value of 6 to 8 indicates a case depth of 2.4 mm ($\frac{6}{64}$ in.) and a fracture grain size of 8. Fine-grained water-hardening tool steels are those with fracture grain sizes (F values) of 8 or more. Deep-hardening steels of this type have P values of 12 or more; medium-hardening steels, 9 to 11; and shallow-hardening steels, 6 to 8.

Distortion and Safety in Hardening. Minimal distortion in heat treating is important for tools that must remain within close size limits. In general, the amount of distortion and the tendency to crack increase as the severity of quenching increases.

Resistance to decarburization is an important factor in determining whether a protective atmosphere is required during heat treating. In a decarburizing atmosphere, the rate of decarburization increases rapidly with increasing austenitizing temperature, and, for a given austenitizing temperature, the depth of decarburization increases in direct proportion to holding time. Some types of tool steel decarburize much more rapidly than others under the same conditions of atmosphere, austenitizing temperature, and time.

Machining Allowances

The standard machining allowance is the recommended total amount of stock that the user should remove from the as-supplied mill form to provide a surface free from imperfections that might adversely affect the response to heat treatment or the ability of tools to perform properly.

The decarburization resulting from oxidation at the exposed surfaces during the forging and rolling of the tool steel is a major factor in determining the amount of stock that should be removed. Although extra care is used in producing tool steels, scale, seams, and other surface imperfections that may be present must be removed.

In addition to the standard machining allowance, sufficient stock must be provided to permit the cleanup of any decarburization or distortion that may occur during final heat treatment. The amount varies with the type of tool steel, the type of heat treating equipment, and the size and shape of the tool.

Group W and group O tool steels are considered highly resistant to decarburization. Group M steels, cobalt-containing group T steels, group D steels, and types H42, A2, and S5 are rated poor for resisting decarburization.

Decarburization during final heat treatment is undesirable because it alters the composition of the surface layer, thereby changing the response to heat treatment of this layer and usually adversely affecting the properties resulting from heat treatment. Decarburization can be controlled or avoided by heat treating in a salt bath or in a controlled atmosphere or vacuum furnace. When heat treating is accomplished in vacuum, a vacuum of 13 to 27 Pa (100 to 200 μm Hg) is satisfactory for most tools if the furnace is in good operating condition and has a very low leak rate. However, it is recommended that a vacuum of 7 to 13 Pa (50 to 100 μm Hg) be used wherever possible.

If special heat-treating equipment is not available, appreciable decarburization can be avoided by wrapping the tool in stainless steel foil. Type 321 stainless steel foil can be used at austenitizing temperatures up to about 1010 °C (1850 °F). Type 309 or 310 foil is required at austenitizing temperatures from 1010 to 1205 °C (1850 to 2200 °F).

P/M Tool Steels

Powder metallurgy (P/M) has become a major process for the manufacture of high-performance tool steels and tool steel products. The items now available include as-compacted or hot-worked billets and bars, semifinished parts, near-net shapes, and indexable cutting tool inserts. The P/M process has been used primarily for the production of advanced high-speed tool steels. However, it is now also being applied to the manufacture of improved cold-work and hot-work tool steels.

For most applications, the P/M tool steels offer distinct advantages over conventional tool steels. As a result of pronounced ingot segregation, conventional tool steels often contain a coarse, nonuniform microstructure accompanied by low transverse properties and problems with size control and hardness uniformity in heat treatment. Rapid solidification of the atomized powders used in P/M tool steels eliminates such segregation and produces a very fine microstructure with a uniform distribution of carbides and nonmetallic inclusions.

For high-speed tool steels, a number of important end-user properties have been improved by powder processing, notably machinability, grindability, dimensional control during heat treatment, and cutting performance under difficult conditions where high edge toughness is essential. Further, the alloying flexibility of the P/M process allows the production of new high-speed tool steels that cannot be made by conventional ingot processes because of segregation-related hot-workability problems.

P/M Processing

Fully dense P/M tool steels are made either from hot isostatically pressed (HIP) gas-atomized tool steel powder or from cold compacted and vacuum sintered water-atomized tool steel powder. In both cases, the resulting billets have a fine, uniform carbide distribution with no segregation.

Powder Production. Tool steel powders are produced by induction melting of virgin raw materials and/or scrap. As mentioned above, gas or water atomization methods are used. Gas-atomized (with argon or nitrogen) tool steel powders have spherical particles (Fig. 10a) with high apparent densities (about 6 g/cm^3). Oxygen content is less than 200 ppm. These powders are hot isostatically pressed into semifabricated shapes of full density. Complex shapes can also be made by cold isostatic pressing (CIP) followed by HIP. Water-atomized tool steel powders have irregularly shaped particles (Fig. 10b) and are suitable for conventional die compaction or CIP, followed by sintering to high or theoretical density.

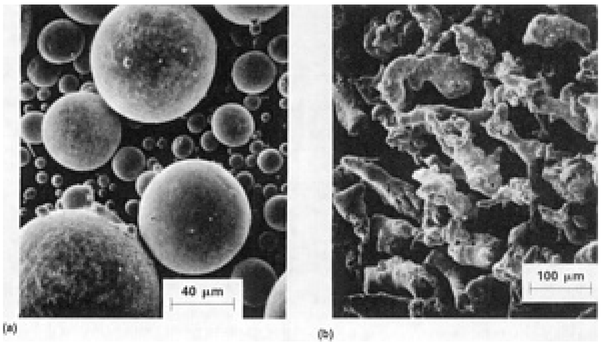

Fig. 10 Scanning electron micrographs of (a) nitrogen-atomized and (b) water-atomized high-speed tool steel powders

Water-atomized high-speed tool steel powders are annealed either in vacuum or hydrogen. Martensite and retained austenite are thereby transformed to a mixture of ferrite and spheroidal carbide. This renders the powder softer and more ductile and suitable for compaction.

HIP of Tool Steels. Since 1970, P/M high-speed tool steel powders have been consolidated to full density by HIP processing. In terms of tonnage, this processing route constitutes the vast majority of P/M high-speed tool steels produced worldwide.

Using the HIP method, the desired chemical composition is melted, and the molten stream is poured into an atomizing chamber where high-pressure gas jets disperse it into spheroidal droplets that are rapidly quenched to ambient temperature. Powder is removed from the atomizing chamber, dried, and screened to obtain the desired size fraction. It is then poured into cylindrical steel cans that are evacuated and sealed. the cans are subsequently heated to a specific temperature and hot isostatically compacted to achieve a fully dense product. Typical processing conditions are consolidated at 1100 °C (2000 °F) at 100 MPa (15 ksi) for 1 h. Compacts are further processed to the desired billet and bar sizes by conventional hot rolling and forging.

A distinguishing feature of P/M high-speed tool steels that have undergone HIP is the uniform distribution and small size of the primary carbides. The same is true of the sulfide inclusions in resulfurized grades. The size distributions of the primary carbides in P/M-produced and conventionally produced T15 have been measured, as shown in Fig. 11. Most of the carbides in gas atomized/HIPed P/M high-speed tool steels are less than about 3 μm, while those in the conventional product cover the entire size range up to about 34 μm, with a median size of 6 μm. Microstructures of P/M and conventionally processed T15 are compared in Fig. 12.

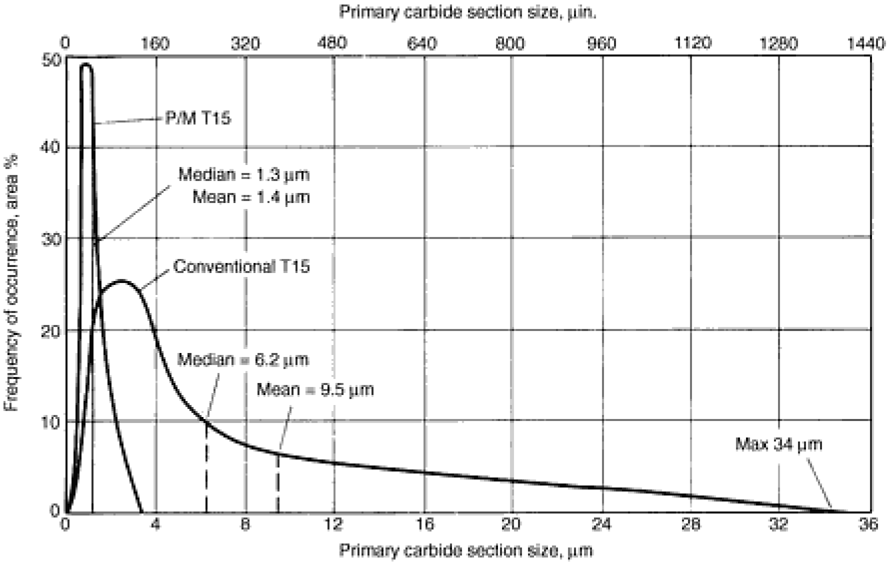

Fig. 11 Primary carbide size distribution of T15 high-speed tool steel produced conventionally and by P/M processing

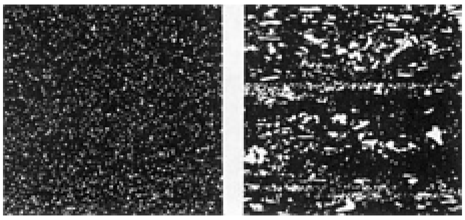

Fig. 12 Comparison of carbide size and distribution in P/M (left) and wrought (right) T15 steel

Pressed-and-Sintered Tool Steels. The use of conventional press-and-sinter technology offers the additional advantage of net shape or near-net shape capability. Current commercial fully dense sintering uses high green strength and compressible water-atomized tool steel powders that are compacted in rigid dies using either uniaxial pressing or in flexible rubber molds using CIP to make green tools and parts (generally, parts are pressed from 70 to 85% of theoretical density). These parts are then sintered in a microprocessor-controlled vacuum furnace near the solidus temperature of the alloy to virtually full density (at least 98% and frequently 99+% of theoretical). Sintering temperatures range from about 1240 to 1260 °C (2260 to 2300 °F). Due to the higher temperatures used in processing, the primary carbides tend to be larger in vacuum-sintered steels than in HIPed tool steels. However, they are still smaller than in conventional tool steels of similar composition.

P/M High-Speed Tool Steels

A large variety of P/M high-speed tool steels are available (Table 7). The P/M process has been applied primarily to standard high-speed tool steels (M2, M3, M4, M35, and so on) that are normally produced by conventional means but have significantly improved toughness and grindability when the P/M process is used. A number of P/M high-speed steels have been developed that cannot be made by conventional methods because of their high carbon, nitrogen, or alloy contents. For example, CPM Rex 76 is a cobalt-rich high-speed steel with exceptional hot hardness and wear resistance, along with greatly increased tool life in different cutting operations. Its high total alloy content (32.5%, compared to 27.8% for T15 and 25% for M42) renders this alloy unforgeable if produced by conventional methods.

Table 7 Chemical compositions of P/M tool steels produced from gas-atomized and hot isostatically pressed powders

Trade name[(a)]	AISI designation	Constituent elements, %								Hardness, HRC
		C	**Cr**	**W**	**Mo**	**V**	**Co**	**S**	**Other**	
ASP 23	M3	1.28	4.20	6.40	5.00	3.10	. . .	. . .	. . .	65-67
ASP 30	. . .	1.28	4.20	6.40	5.00	3.10	8.5	. . .	. . .	66-68
ASP 60	. . .	2.30	4.00	6.50	7.00	6.50	10.50	. . .	. . .	67-69
CPM Rex M2HCHS	M2	1.00	4.15	6.40	5.00	2.00	. . .	0.27	. . .	64-66
CPM Rex M3HCHS	M3	1.30	4.00	6.25	5.00	3.00	. . .	0.27	. . .	65-67

CPM Rex M4	M4	1.35	4.25	5.75	4.50	4.00	. . .	0.06	. . .	64-66
CPM Rex M4HS	M4	1.35	4.25	5.75	4.50	4.00	. . .	0.22	. . .	64.66
CPM Rex M35HCHS	M35	1.00	4.15	6.00	5.00	2.00	5.0	0.27	. . .	65-67
CPM Rex M42	M42	1.10	3.75	1.50	9.50	1.15	8.0	. . .	. . .	66-68
CPM Rex 45	. . .	1.30	4.00	6.25	5.00	3.00	8.25	0.03	. . .	66-68
CPM Rex 45	. . .	1.30	4.00	6.25	5.00	3.00	8.25	0.22	. . .	66-68
CPM Rex 20	M62	1.30	3.75	6.25	10.50	2.00	. . .	. . .	. . .	66-68
CPM Rex 25	M61	1.80	4.00	12.50	6.50	5.00	. . .	. . .	. . .	67-69
CPM Rex T15	T15	1.55	4.00	12.25	. . .	5.00	5.0	0.06	. . .	65-67
CPM Rex T15HS	T15	1.55	4.00	12.25	. . .	5.00	5.0	0.22	. . .	65-67
CPM Rex 76	M48	1.50	3.75	10.0	5.25	3.10	9.00	0.06	. . .	67-69
CPM Rex 76HS	M48	1.50	3.75	10.0	5.25	3.10	9.00	0.22	. . .	67-69
Cold-work tool steels										
CPM 9V	. . .	1.78	5.25	. . .	1.30	9.00	. . .	0.03	. . .	53-55
CPM 10V	. . .	2.45	5.25	. . .	1.30	9.75	. . .	0.07	. . .	60-62
CPM 15V	. . .	3.40	5.00	. . .	1.30	14.50	. . .	. . .	. . .	62-64
CPM 440V	. . .	2.15	17.50	. . .	0.50	5.75	. . .	. . .	. . .	57-59
Vanadis 4	. . .	1.50	8.00	. . .	1.50	4.00	. . .	. . .	. . .	59-63
Vanadis 10	. . .	2.90	8.00	. . .	1.50	9.80	. . .	. . .	1.0Si; 0.5Mn	60-62
Hot-work tool steels										
CPM H13	H13	0.40	5.00	. . .	1.30	1.05	. . .	. . .	. . .	42-48

CPM H19	H19	0.40	4.25	4.25	0.40	2.10	4.25	. . .	. . .	44-52
CPM H19V	. . .	0.80	4.25	4.25	0.40	4.00	4.25	. . .	. . .	44-56

(a) HCHS, high carbon, high sulfur; HS, high sulfur

The machinability as well as the grindability of high-speed steels are important factors that affect alloy selection and the cost of a finished tool. In general, the machinability of P/M high-speed tool steels in the annealed condition is comparable to or, in many cases, superior to that of conventional high-speed tool steels of similar composition.

An important advantage of the P/M process is that the machinability of P/M tool steels can be improved by increasing their sulfur contents to levels much higher than conventional, without sacrificing toughness or cutting performance. As indicated in Table 7, several P/M high-speed tool steels are available that contain as much as 0.30% S (see, for example, grades M2HCHS and M3HCHS). Depending on specific conditions, the highly resulfurized P/M tool steels can offer as much as a 30% improvement in machinability over P/M tool steels with lower sulfur levels or conventional high-speed tool steels of similar composition.

The machinability advantage of resulfurized P/M tool steels largely relates to the uniform distribution of the carbides and sulfides in their microstructures. The carbides and the sulfides in conventional steels are typically segregated in bands and are larger than those of the P/M steel. Because of the small size and uniform distribution of the sulfides, more sulfur (with a corresponding greater improvement in machinability) can be used in P/M tool steels than in conventional tool steels before hot workability or mechanical properties are degraded.

The grindability of P/M high-speed steels is also superior to that of conventional high-speed steel of the same composition because of the small size and uniform distribution of carbides in P/M steels, regardless of bar size. The relative grindability of several conventional and P/M high-speed tool steels is illustrated in Fig. 13. The grinding ratio is clearly superior for the P/M tool steels, particularly those with high sulfur contents. As expected, the grinding ratio generally decreases for both the conventional and P/M tool steels as their alloy and carbon contents increase.

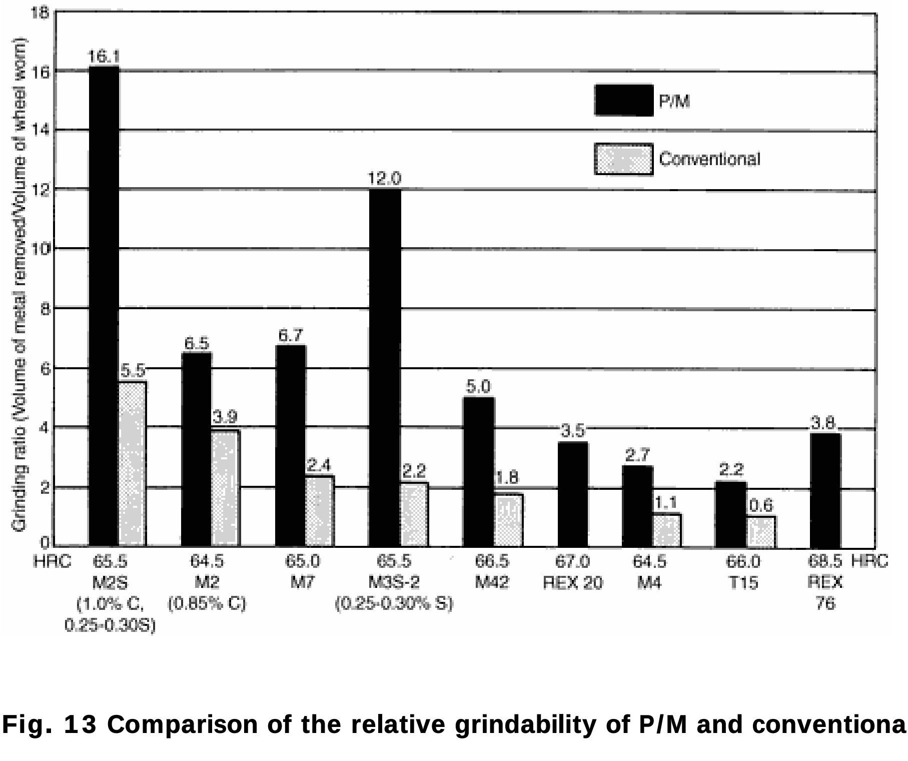

Fig. 13 Comparison of the relative grindability of P/M and conventional high-speed tool steels

Toughness, Hardness, and Wear Resistance. The cutting performance of high-speed steels is primarily determined by their wear, their resistance to tempering at operating temperatures, and their toughness.

Wear resistance is generally a function of hardness and of the type, volume, and shape of the primary carbides present in the tool. In this respect, the higher hardness attainable with P/M high-speed tool steels, along with the greater amount of alloy carbides that can be included in these steels, constitutes a significant advantage over conventional high-speed steels.

Temper resistance, or hot hardness, is largely determined by the composition and growth of the secondary hardening carbides and is promoted by vanadium, molybdenum, and cobalt. These elements can be used in larger amounts in P/M high-speed steels than in conventional steels without degrading properties.

Toughness of the high-speed steels is determined by the state of tempering of the matrix and the spatial and size distribution of the primary carbides. Here again, the uniform distribution and small size of the carbides in P/M high-speed steels represents an important toughness advantage.

P/M Cold- and Hot-Work Tool Steels

P/M Cold-Work Tool Steels. A number of improved, high-vanadium P/M tool steels designed for high-wear and cold-work applications are commercial available. The chemical compositions of six representative P/M cold-work grades are given in Table 7. As with P/M high-speed tool steels, the more uniform microstructure of the P/M cold-work steels yields better toughness (Fig. 14). This is very important in cold-work tooling, because it allows higher hardnesses to be used with associated improvements in yield strength and wear resistance. Further, substantial improvements in wear resistance have been realized by using higher vanadium contents in P/M cold-work tool steels than is practical in conventional cold-work tool steels.

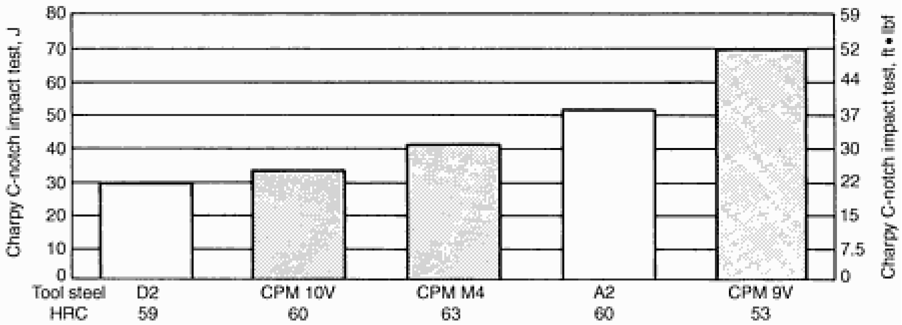

Fig. 14 Charpy C-notch impact properties of P/M and conventional tool steels at indicated hardness for cold-work applications

P/M Hot-Work Tool Steels. The absence of segregation in P/M tool steels makes them very attractive for hot-work tool and die applications, because a frequent cause of premature failure of large die casting dies is thermal fatigue attributed to segregation and nonheterogeneous microstructures. The compositions of three P/M hot-work tool steels now commercial available are given in Table 7. Two are P/M versions of standard H13 and H19 hot-work tool steels that have more uniform properties and equivalent or better toughness when made by P/M methods. The third is a high-vanadium modification of standard H19 with improved toughness and wear resistance.

Precision-Cast Tool Steels

Precision casting of tools to nearly finished size offers important cost advantages through reductions in waste and machining. Casting is particularly advantageous when patternmaking costs can be distributed over a large number of tools.

Experience with cast forging and extrusion dies has shown that cast tools are more resistant to heat checking; minute cracks do occur, but they grow at much lower rates than in wrought material of the same grade and hardness. Slower propagation of thermal-fatigue cracks generally extends die life significantly. Mechanical testing of cast and wrought H13 indicates that yield and tensile strengths are virtually identical from room temperature to 600 °C (1100 °F), but that ductility is moderately lower in cast material. Hot hardness of cast H13 is higher than that of wrought H13 at temperatures above about 300 °C (about 600 °F); this hardness advantage increases with temperature and measures about eight points on the HRC scale at 650 °C (1200 °F).

Because cast dies exhibit uniform properties in all directions, no problem of directionality (anisotropy) exists. Dimensional control of castings is very consistent after an initial die is made and any necessary corrections are incorporated in the pattern. Reasonable finishing allowances are 0.25 to 0.38 mm (0.010 to 0.015 in.) on the impression faces, 0.8 to 1.6 mm ($\frac{1}{32}$ to $\frac{1}{16}$ in.) at the parting line of the mold, and 1.6 to 3.2 mm ($\frac{1}{16}$ to $\frac{1}{8}$ in.) on the back and outside surfaces. The hot-work tool steels most commonly cast include H12, H13, H21, and H25.

Specialty Tool Steels

Through-Hardening Stainless Steels. Type 420 martensitic stainless steel (and modifications of this alloy) is commonly used for injection molds for all thermoplastic materials. It is particularly adaptable for molding vinyls or other corrosive plastics, or when the atmospheric or storage conditions are unusually severe, because it does not require chromium plating to resist these types of corrosive attack. Other stainless steels used for plastic molds include type 414, free-machining grade 420F, and Elmax, a high-hardness (58 to 60 HRC) wear-resistant P/M grade. Chemical compositions of these stainless steels are given in Table 8.

Table 8 Chemical compositions of martensitic stainless steel plastic mold materials

Alloy	Composition, wt%							
	C	**Si**	**Mn**	**Cr**	**Ni**	**Mo**	**V**	**S**
414	0.15	1.0	1.0	12.5	1.9	. . .	. . .	. . .
420 mod	0.38	0.9	0.5	13.6	. . .	. . .	0.3	. . .
420F mod	0.33	0.35	1.4	16.7	. . .	. . .	. . .	0.12
Elmax[(a)]	1.7	0.8	0.3	17.0	. . .	1.0	3.0	. . .

(a) P/M stainless steel produced by hot isostatic pressing of gas-atomized stainless steel powder

Type 440C martensitic stainless steel, both in wrought and P/M versions, is also used for some cold-work applications. CPM 440V is a high-vanadium, high-chromium tool steel for applications requiring both high wear resistance and good corrosion resistance. The composition of this material (Table 7) is essentially that of wrought type 440C to which about 5.75% V and increased carbon have been added to improve wear resistance.

Maraging Steels. Certain high-nickel maraging steels are being used for special noncutting tool applications; 18Ni(250) is the type most frequently used. However, for the most demanding applications, the higher-strength 18Ni(300) is often preferred. For applications requiring maximum abrasion resistance, any of the maraging steels can be nitrided.

Maraging steels achieve full hardness--nominally 500 HRC for 18Ni(250), 54 HRC for 18Ni(300), and 58 HRC for 18Ni(350)--by a simple aging treatment, usually 3 h at about 480 °C (900 °F). Because hardening does not depend on cooling rate, full hardness can be developed uniformly in massive sections, with almost no distortion. Decarburization is of no concern in these alloys because they do not contain carbon as an alloying element. If the long-time service temperature exceeds the aging temperature, maraging steels overage with a significant drop in hardness.

The 18Ni(250) grade is used for aluminum die-casting dies and cores, aluminum hot forging dies, dies for molding plastics, and various support tooling used in extrusion of aluminum. In die casting of aluminum, maraging steel dies can be used at higher hardness than is possible for dies made of H13 tool steel because maraging steel is not as prone to heat checking. Because the aging process results in very little size change, it is possible to machine the intricate impressions for plastic molding dies to final size prior to final hardening.

For molding extremely abrasive types of plastics, the higher surface hardness provided by 18Ni(300) maraging steel is desirable.

Wrought Stainless Steels: Selection and Application

Introduction

STAINLESS STEELS are iron-base alloys that contain a minimum of approximately 11% Cr, the amount needed to prevent the formation of rust in unpolluted atmospheres (hence the designation stainless). Few stainless steels contain more than 30% Cr or less than 50% Fe. They achieve their stainless characteristics through the formation of an invisible and adherent chromium-rich oxide surface film. This oxide forms and heals itself in the presence of oxygen. Other elements added to improve particular characteristics include nickel, molybdenum, copper, titanium, aluminum, silicon, niobium, nitrogen, sulfur, and selenium. Carbon is normally present in amounts ranging from less than 0.03% to over 1.0% in certain martensitic grades. Figure 1 provides a useful summary of some of the compositional and property linkages in the stainless steel family.

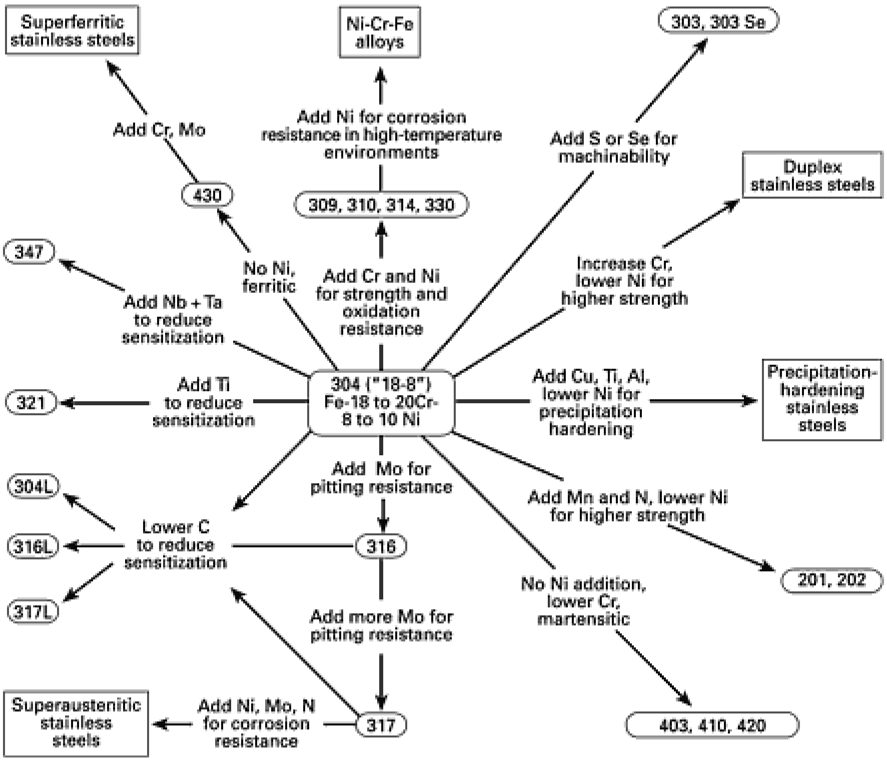
Superferritic stainless steels
Ni-Cr-Fe alloys
303, 303 Se
Add Cr, Mo
Add Ni for corrosion resistance in high-temperature environments
Add S or Se for machinability
Duplex stainless steels
430
309, 310, 314, 330
347
No Ni, ferritic
Add Cr and Ni for strength and oxidation resistance
Increase Cr, lower Ni for higher strength
Add Nb + Ta to reduce sensitization
321
Add Ti to reduce sensitization
304 ("18-8") Fe-18 to 20Cr-8 to 10 Ni
Add Cu, Ti, Al, lower Ni for precipitation hardening
Precipitation-hardening stainless steels
304L
Add Mo for pitting resistance
Add Mn and N, lower Ni for higher strength
316L
Lower C to reduce sensitization
316
201, 202
317L
No Ni addition, lower Cr, martensitic
Add more Mo for pitting resistance
Superaustenitic stainless steels
Add Ni, Mo, N for corrosion resistance
317
403, 410, 420

Fig. 1 Compositional and property linkages in the stainless steel family of alloys

Production of stainless steels is a two-stage process involving the melting of scrap and ferro-alloys in an electric-arc furnace followed by refining by oxygen-inert gas injection (argon oxygen decarburization) or oxygen injection under vacuum (vacuum oxygen decarburization) to adjust carbon content and remove impurities. (Both of these processes are described in the Section "Iron and Steelmaking Practices" in this Handbook.) The refined molten metal is then poured into molds to form ingots, followed later by blooming or slabbing, or is poured directly into a continuous casting machine to form slabs, blooms, or billets. Cast ingots can be rolled or forged; and flat products (sheet, strip, and plate) can be produced from continuously cast slabs. The rolled product can be drawn, bent, extruded, or spun. Stainless steels can be further shaped by machining, and they can be joined by welding, brazing, soldering, and adhesive bonding. Stainless steels can also be used as an integral cladding on plain carbon or low-alloy steels, as well as some nonferrous metals and alloys.

Stainless steels are used in a wide variety of applications. Most of the structural applications occur in the chemical and power engineering industries, which account for more than a third of the market for stainless steel products (see the following table). These applications include an extremely diversified range of uses, including nuclear reactor vessels, heat exchangers, oil industry tubulars, components for chemical processing and pulp and paper industries, furnace parts, and boilers used in fossil fuel electric power plants. The relative importance of the major fields of application for stainless steel products are as follows:

Application	Percentage
Industrial equipment	
Chemical and power engineering	34
Food and beverage industry	18
Transportation	9
Architecture	5
Consumer goods	
Domestic appliances, household utensils	28
Small electrical and electronic appliances	6

Some of these applications involve exposure to either elevated or cryogenic temperatures; austenitic stainless steels (see the following discussion) are well suited to either type of service.

Designations for Stainless Steels

In the United States, wrought grades of stainless steels are generally designated by the American Iron and Steel Institute (AISI) numbering system, the Unified Numbering System (UNS), or the proprietary name of the alloy. In addition, designation systems have been established by most of the major industrial nations. Of the two institutional numbering systems used in the U.S., AISI is the older and more widely used. Most of the grades have a three-digit designation; the 200 and 300 series are generally austenitic stainless steels, whereas the 400 series are either ferritic or martensitic. Some of the grades have a one- or two-letter suffix that indicates a particular modification of the composition.

The UNS system includes a considerably greater number of stainless steels than AISI because it incorporates all of the more recently developed stainless steels. The UNS designation for a stainless steel consists of the letter S, followed by a five-digit number. For those alloys that have an AISI designation, the first three digits of the UNS designation usually correspond to an AISI number. When the last two digits are 00, the number designates a basic AISI grade. Modifications of the basic grades use two digits other than zeroes. For stainless steels that contain high nickel contents (~25 to 35% Ni), the UNS designation consists of the letter N followed by a five-digit number. Examples include N08020 (20Cb-3), N08024 (20Mo-4), N08026 (20Mo-6), N08366 (AL-6X), and N08367 (AL-6XN). Although classified as nickel-base alloys by the UNS system, the previously mentioned materials constitute the "superaustenitic" category of stainless steel shown in Fig. 1 and described in the following section "Classification of Stainless Steels."

Classification of Stainless Steels

Stainless steels can be divided into five families. Four are based on the characteristic crystallographic structure/microstructure of the alloys in the family: martensitic, ferritic, austenitic, or duplex (austenitic plus ferritic). The fifth family, the precipitation-hardenable alloys, is based on the type of heat treatment used, rather than microstructure.

Martensitic Stainless Steels

Characteristics and Compositions. Martensitic stainless steels are essentially Fe-Cr-C alloys that possess body-centered tetragonal (bct) crystal structure (martensitic) in the hardened condition. They are ferromagnetic, hardenable by heat treatments, and generally resistant to corrosion only in relatively mild environments. Chromium content is generally in the range of 10.5 to 18%, and carbon content can exceed 1.2%. The chromium and carbon contents are balanced to ensure a martensitic structure. Elements such as niobium, silicon, tungsten, and vanadium can be added to modify the tempering response after hardening. Small amounts of nickel can be added to improve corrosion resistance in some media and to improve toughness. Sulfur or selenium is added to some grades to improve machinability. Table 1 provides chemical compositions for standard (AISI) and nonstandard grades.

Table 1 Chemical compositions of martensitic stainless steels

UNS No.	Type/designation	Composition[(a)], %							
		C	**Mn**	**Si**	**Cr**	**Ni**	**P**	**S**	**Other**
Standard (AISI) grades									
S40300	403	0.15	1.00	0.50	11.5-13.0	. . .	0.04	0.03	. . .
S41000	410	0.15	1.00	1.00	11.5-13.5	. . .	0.04	0.03	. . .
S41400	414	0.15	1.00	1.00	11.5-13.5	1.25-2.50	0.04	0.03	. . .
S41600	416	0.15	1.25	1.00	12.0-14.0	. . .	0.06	0.15 min	0.6 Mo[(b)]
S41623	416Se	0.15	1.25	1.00	12.0-14.0	. . .	0.06	0.06	0.15 min Se
S42000	420	0.15 min	1.00	1.00	12.0-14.0	. . .	0.04	0.03	. . .
S42020	420F	0.15 min	1.25	1.00	12.0-14.0	. . .	0.06	0.15 min	0.6 Mo[(b)]
S42200	422	0.20-0.25	1.00	0.75	11.5-13.5	0.5-1.0	0.04	0.03	0.75-1.25 Mo; 0.75-1.25 W; 0.15-0.3 V

S43100	431	0.20	1.00	1.00	15.0-17.0	1.25-2.50	0.04	0.03	. . .
S44002	40A	0.60-0.75	1.00	1.00	16.0-18.0	. . .	0.04	0.03	0.75 Mo
S44003	440B	0.75-0.95	1.00	1.00	16.0-18.0	. . .	0.04	0.03	0.75 Mo
S44004	440C	0.95-1.20	1.00	1.00	16.0-18.0	. . .	0.04	0.03	0.75 Mo
Nonstandard grades									
S41008	Type 410S	0.08	1.00	1.00	11.5-13.5	0.60	0.040	0.030	. . .
S41040	Type 410 Cb (XM-30)	0.15	1.00	1.00	11.5-13.5	. . .	0.040	0.030	0.05-0.20 Nb
DIN 1.4935(c)	HT9	0.17-0.23	0.30-0.80	0.10-0.50	11.0-12.5	0.30-0.80	0.035	0.035	0.80-1.20 Mo; 0.25-0.35 V; 0.4-0.6 W
S41610	416 Plus X (XM-6)	0.15	1.5-2.5	1.00	12.0-14.0	. . .	0.060	0.15 min	0.6 Mo
S41800	Type 418 (Greek Ascolloy)	0.15-0.20	0.50	0.50	12.0-14.0	1.8-2.2	0.040	0.030	2.5-3.5 W
S42010	TrimRite	0.15-0.30	1.00	1.00	13.5-15.0	0.25-1.00	0.040	0.030	0.40-1.00 Mo
S42023	Type 429 F Se	0.3-0.4	1.25	1.00	12.0-14.0	. . .	0.060	0.060	0.15 min Se; 0.6 Zr; 0.6 Cu
S42300	Lapelloy	0.27-0.32	0.95-1.35	0.50	11.0-12.0	0.50	0.025	0.025	2.5-3.0 Mo; 0.2-0.3 V
S44020	Type 440 F	0.95-1.20	1.25	1.00	16.0-18.0	0.75	0.040	0.10-0.35	0.08 N
S44023	Type 440 F Se	0.95-1.20	1.25	1.00	16.0-18.0	0.75	0.040	0.030	0.15 min Se; 0.60 Mo

(a) Single values are maximum values unless otherwise indicated.

(b) Optional.

(c) German (DIN) specification

Properties and Applications. The most commonly used alloy within the martensitic stainless steel family is type 410, which contains approximately 12 wt% Cr and 0.1 wt% C to provide strength. The carbon level and, consequently, strength increase in the 420, 440A, 440B, and 440C alloy series. The latter three alloys, in particular, have an increased chromium level in order to maintain corrosion resistance. Molybdenum can be added to improve mechanical properties or corrosion resistance, as it is in type 422 stainless steel. Nickel can be added for the same reasons in types 414 and 431. When higher chromium levels are used to improve corrosion resistance, nickel also serves to maintain the desired microstructure and to prevent excessive free ferrite. The limitations on the alloy content required to maintain the desired fully martensitic structure restrict the obtainable corrosion resistance to moderate levels.

In the annealed condition, martensitic stainless steels have a tensile yield strength of approximately 275 MPa (40 ksi) and can be moderately hardened by cold working. However, martensitic alloys are typically heat treated by both hardening and tempering to yield strength levels up to 1900 MPa (275 ksi), depending primarily on carbon level. These alloys have good ductility and toughness properties, which decrease as strength increases. Depending on the heat treatment, hardness values range from approximately 150 HB (80 HRB) for materials in the annealed condition to levels greater than 600 HB (58 HRC) for fully hardened materials.

Martensitic stainless steels are specified when the application requires good tensile strength, creep, and fatigue strength properties, in combination with moderate corrosion resistance and heat resistance up to approximately 650 °C (1200 °F). In the United States, low- and medium-carbon martensitic steels (for example, type 410 and modified versions of this alloy) have been used primarily in steam turbines, jet engines, and gas turbines. In Europe, alloy HT9 (12Cr-1Mo-0.3V) has been widely used in elevated-temperature, pressure-containment applications, including steam piping and steam generator reheater and superheater tubing used in fossil fuel power plants. Type 420 and similar alloys are used in cutlery, valve parts, gears, shafts, and rollers. Other applications for higher carbon-level grades (type 440 grades) include cutlery, surgical and dental instruments, scissors, springs, valves, gears, shafts, cams, and ball bearings.

Ferritic Stainless Steels

Characteristics and Compositions. Ferritic stainless steels are essentially iron-chromium alloys with body-centered cubic (bcc) crystal structures. Chromium content is usually in the range of 11 to 30%. Some grades may contain molybdenum, silicon, aluminum, titanium, and niobium to confer particular characteristics. Sulfur or selenium can be added to improve machinability. Table 2 lists compositions of ferritic stainless steels.

Table 2 Chemical compositions of ferritic stainless steels

UNS No.	Type/designation	Composition[(a)], wt%					
		C	**Cr**	**Mo**	**Ni**	**N**	**Other**
First-generation alloys							
S42900	429	0.12	14.0-16.0	. . .	. . .	. . .	. . .
S43000	430	0.12	16.0-18.0	. . .	. . .	. . .	. . .
S43020	430F	0.12	16.0-18.0	0.6	. . .	. . .	0.06 P; 0.15 min S

S43023	430FSe	0.12	16.0-18.0	. . .	. . .	. . .	0.15 min Se
S43400	434	0.12	16.0-18.0	0.75-1.25	. . .	. . .	. . .
S43600	436	0.12	16.0-18.0	0.75-1.25	. . .	. . .	Nb + Ta = 5 × %C min
S44200	442	0.20	18.0-23.0	. . .	. . .	. . .	. . .
S44600	446	0.20	23.0-27.0	. . .	. . .	. . .	. . .
Second-generation alloys							
S40500	405	0.08	11.5-14.5	. . .	. . .	. . .	0.10-0.30 Al
S40900	409	0.08	10.5-11.75	. . .	0.5	. . .	Ti = 6 × C min to 0.75 max
. . .	409Cb	0.02(b)	12.5(b)	. . .	0.2(b)	. . .	0.4 Nb(b)
S44100	441	0.02(b)	18.0(b)	. . .	0.3(b)	. . .	0.7 Nb(b), 0.3 Ti(b)
. . .	AL433	0.02(b)	19.0(b)	. . .	0.3(b)	. . .	0.4 Nb(b), 0.5 Si(b), 0.4 Cu(b)
. . .	AL446	0.01(b)	11.5(b)	. . .	0.2(b)	. . .	0.2 Nb(b), 0.1 Ti(b)
. . .	AL468	0.01(b)	18.2(b)	. . .	0.2(b)	. . .	0.2 Nb(b), 0.1 Ti(b)
. . .	YUS436S	0.01(b)	17.4(b)	1.2(b)	. . .	. . .	0.2 Ti(b)
S43035	439	0.07	17.00-19.00	. . .	0.5	. . .	Ti = 0.20 + 4 (C + N) min to 1.0 max
. . .	12SR	0.2	12.0	. . .	. . .	. . .	1.2 Al; 0.3 Ti
. . .	18SR	0.04	18.0	. . .	. . .	. . .	2.0 Al; 0.4 Ti
K41970	406	0.06	12.0-14.0	. . .	0.5	. . .	2.75-4.25 Al; 0.6 Ti

UNS No.	Type/designation	C	Cr	Fe	Mo	Ni	N	Other
Third-generation alloys								
S44626	26-1Ti	0.02	26	bal	1	0.25	0.025	0.5Ti

S44400	Type 444	0.02	18	bal	2	0.4	0.02	0.5Ti
S44660	SEA-CURE	0.02	27.5	bal	3.4	1.7	0.025	0.5Ti
S44635	Nu Monit	0.025	25	bal	4	4	0.025	0.4Ti
S44735	AL 29-4C	0.030	29	bal	4	1.0	0.045	(Nb + Ti)
S44726	E-Brite 26-1	0.002	26	bal	1	0.1	0.01	0.1Nb
S44800	AL 29-4-2	0.005	29	bal	4	2	0.01	. . .
. . .	SHOMAC 26-4	0.003	26	bal	4	. . .	0.005	. . .
. . .	SHOMAC 30-2	0.003	30	bal	2	0.18	0.007	. . .
. . .	YUS 190L	0.004	19	bal	2	. . .	0.0085	0.15Nb

(a) Single values are maximum unless otherwise indicated.

(b) Typical value

The ferritic alloys are ferromagnetic. They can have good ductility and formability, but high-temperature strengths are relatively poor compared to those of the austenitic grades. Toughness may be somewhat limited at low temperatures and in heavy sections. Unlike the martensitic stainless steels, the ferritic stainless steels cannot be strengthened by heat treatment. Also, because the strain-hardening rates of ferrite are relatively low and cold work significantly lowers ductility, the ferritic stainless steels are not often strengthened by cold work.

Properties and Applications. Typical annealed yield and tensile strengths for ferritic stainless steels are 35 to 55 ksi (240 to 380 MPa) and 60 to 85 ksi (415 to 585 MPa), respectively. Ductilities tend to range between 20 and 35%. Higher strengths, up to 75 ksi (515 MPa) for yield strength and 95 ksi (655 MPa) for tensile strength, are obtained in the more highly alloyed "superferritic" steels shown in Fig. 1.

Whereas the martensitic stainless steels offer only moderate corrosion resistance, that of the ferritic stainless steels can range from moderate for the low-to-medium, chromium-content alloys to outstanding for the superferritics such as type 444 and UNS No. S44627, S44635, S44660, S44700, and S44800. The low-chromium (11%) alloys, such as types 405 and 409, have fair corrosion and oxidation resistance and good fabricability at low cost. Type 409, the most widely used ferritic stainless steel, has gained wide acceptance for use in automotive exhaust systems. The intermediate-chromium (16 to 18%) alloys include type 430, which resists mild oxidizing acids and organic acids and is used in food-handling equipment, and type 434, which includes a molybdenum addition for improved corrosion resistance and is used for automotive trim. The high-chromium (19 to 30%) alloys, which include types 442 and 446 as well as the superferritics, are used for applications that require a high level of corrosion and oxidation resistance. By controlling interstitial element content via argon oxygen decarburization (AOD) processing, it is possible to produce grades with unusually high chromium and molybdenum (up to 4.5%) contents and very low carbon contents (as low as 0.01%). Such highly alloyed superferritics offer exceptional resistance to localized corrosion induced by exposure to aqueous chlorides. Localized corrosion, such as pitting, crevice corrosion, and stress-corrosion cracking (SCC) are problems that plague many austenitic stainless steels. Therefore, the superferritics are often used in heat exchangers and piping systems for chloride-bearing aqueous solutions and seawater.

Austenitic Stainless Steels

Characteristics and Compositions. Austenitic stainless steels constitute the largest stainless family in terms of number of alloys and usage. Like the ferritic alloys, they cannot be hardened by heat treatment. However, their similarity ends there. The austenitic stainless steels are essentially nonmagnetic in the annealed condition and can be hardened only by cold working. They usually possess excellent cryogenic properties and good high-temperature strength and oxidation resistance. Chromium content generally varies from 16 to 26%; nickel content is less than or equal to approximately 35%; and manganese content is less than or equal to 15%. The 200 series steels contain nitrogen, 4 to 15% Mn, and lower nickel contents (up to 7% Ni). The 300 series steels contain larger amounts of nickel and up to 2% Mn. Molybdenum, copper, silicon, aluminum, titanium, and niobium can be added to confer certain characteristics, such as halide pitting resistance or oxidation resistance. Table 3 provides chemical compositions for standard (AISI) and nonstandard grades.

Table 3 Chemical compositions of austenitic stainless steels

UNS No.	Type/designation	Composition[a], %							
		C	**Mn**	**Si**	**Cr**	**Ni**	**P**	**S**	**Other**
Standard (AISI) grades									
S20100	201	0.15	5.5-7.5	1.00	16.0-18.0	3.5-5.5	0.06	0.03	0.25 N
S20200	202	0.15	7.5-10.0	1.00	17.0-19.0	4.0-6.0	0.06	0.03	0.25 N
S20500	205	0.12-0.25	14.0-15.5	1.00	16.5-18.0	1.0-1.75	0.06	0.03	0.32-0.40 N
S30100	301	0.15	2.0	1.00	16.0-18.0	6.0-8.0	0.045	0.03	. . .
S30200	302	0.15	2.0	1.00	17.0-19.0	8.0-10.0	0.045	0.03	. . .
S30215	302B	0.15	2.0	2.0-3.0	17.0-19.0	8.0-10.0	0.045	0.03	. . .
S30300	303	0.15	2.0	1.00	17.0-19.0	8.0-10.0	0.20	0.15 min	0.6 Mo[b]
S30323	303Se	0.15	2.0	1.00	17.0-19.0	8.0-10.0	0.20	0.06	0.15 min Se
S30400	304	0.08	2.0	1.00	18.0-20.0	8.0-10.5	0.045	0.03	. . .
S30409	304H	0.04-0.10	2.0	1.00	18.0-20.0	8.0-10.5	0.045	0.03	. . .

S30403	304L	0.03	2.0	1.00	18.0-20.0	8.0-12.0	0.045	0.03	. . .
S30453	304LN	0.03	2.0	1.00	18.0-20.0	8.0-12.0	0.045	0.03	0.10-0.16 N
S30430	302Cu	0.08	2.0	1.00	17.0-19.0	8.0-10.0	0.045	0.03	3.0-4.0 Cu
S30451	304N	0.08	2.0	1.00	18.0-20.0	8.0-10.5	0.045	0.03	0.10-0.16 N
S30500	305	0.12	2.0	1.00	17.0-19.0	10.5-13.0	0.045	0.03	. . .
S30800	308	0.08	2.0	1.00	19.0-21.0	10.0-12.0	0.045	0.03	. . .
S30900	309	0.20	2.0	1.00	22.0-24.0	12.0-15.0	0.045	0.03	. . .
S30908	309S	0.08	2.0	1.00	22.0-24.0	12.0-15.0	0.045	0.03	. . .
S31000	310	0.25	2.0	1.50	24.0-26.0	19.0-22.0	0.045	0.03	. . .
S31008	310S	0.08	2.0	1.50	24.0-26.0	19.0-22.0	0.045	0.03	. . .
S31400	314	0.25	2.0	1.5-3.0	23.0-26.0	19.0-22.0	0.045	0.03	. . .
S31600	316	0.08	2.0	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mo
S31620	316F	0.08	2.0	1.00	16.0-18.0	10.0-14.0	0.20	0.10 min	1.75-2.5 Mo
S31609	316H	0.04-0.10	2.0	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mo
S31603	316L	0.03	2.0	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mo
S31653	316LN	0.03	2.0	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mo; 0.10-0.16 N

S31651	316N	0.08	2.0	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mo; 0.10-0.16 N
S31700	317	0.08	2.0	1.00	18.0-20.0	11.0-15.0	0.045	0.03	3.0-4.0 Mo
S31703	317L	0.03	2.0	1.00	18.0-20.0	11.0-15.0	0.045	0.03	3.0-4.0 Mo
S32100	321	0.08	2.0	1.00	17.0-19.0	9.0-12.0	0.045	0.03	5 × %C min Ti
S32109	321H	0.04-0.10	2.0	1.00	17.0-19.0	9.0-12.0	0.045	0.03	5 × %C min Ti
N08330	330	0.08	2.0	0.75-1.5	17.0-20.0	34.0-37.0	0.04	0.03	. . .
S34700	347	0.08	2.0	1.00	17.0-19.0	9.0-13.0	0.045	0.03	10 × %C min Nb
S34709	347H	0.04-0.10	2.0	1.00	17.0-19.0	9.0-13.0	0.045	0.03	8 × %C min, 1.0 max Nb
S34800	348	0.08	2.0	1.00	17.0-19.0	9.0-13.0	0.045	0.03	0.2 Co; 10 × %C min Nb; 0.10 Ta
S34809	348H	0.04-0.10	2.0	1.00	17.0-19.0	9.0-13.0	0.045	0.03	0.2 Co; 10 × %C min, 1.0 max Nb; 0.10 Ta
S38400	384	0.08	2.0	1.00	15.0-17.0	17.0-19.0	0.045	0.03	. . .
Nonstandard grades									
S20161	Gall-Tough	0.15	4.00-6.00	3.00-4.00	15.0-18.0	4.00-6.00	0.040	0.040	0.08-0.20 N
S20300	203 EZ (XM-1)	0.08	5.0-6.5	1.00	16.0-18.0	5.0-6.5	0.040	0.18-0.35	0.5 Mo; 1.75-2.25 Cu
S20910	Nitronic 50 (XM-19)	0.06	4.0-6.0	1.00	20.5-23.5	11.5-13.5	0.040	0.030	1.5-3.0 Mo; 0.2-0.4 N; 0.1-0.3 Nb; 0.1-0.3 V
S21400	Tenelon (XM-31)	0.12	14.5-16.0	0.3-1.0	17.0-18.5	0.75	0.045	0.030	0.35 N

S21460	Cryogenic Tenelon (XM-14)	0.12	14.0-16.0	1.00	17.0-19.0	5.0-6.0	0.060	0.030	0.35-0.50 N
S21500	Esshete 1250	0.15	5.5-7.0	1.20	14.0-16.0	9.0-11.0	0.040	0.030	0.003-0.009 B; 0.75-1.25 Nb; 0.15-0.40 V
S21600	Type 216 (XM-17)	0.08	7.5-9.0	1.00	17.5-22.0	5.0-7.0	0.045	0.030	2.0-3.0 Mo; 0.25-0.50 N
S21603	Type 216 L (XM-18)	0.03	7.5-9.0	1.00	17.5-22.0	7.5-9.0	0.045	0.030	2.0-3.0 Mo; 0.25-0.50 N
S21800	Nitronic 60	0.10	7.0-9.0	3.5-4.5	16.0-18.0	8.0-9.0	0.040	0.030	0.08-0.18 N
S21900	Nitronic 40 (XM-10)	0.08	8.0-10.0	1.00	19.0-21.5	5.5-7.5	0.060	0.030	0.15-0.40 N
S21904	21-6-9 LC	0.04	8.00-10.00	1.00	19.00-21.50	5.50-7.50	0.060	0.030	0.15-0.40 N
S24000	Nitronic 33 (18-3 Mn)	0.08	11.50-14.50	1.00	17.0-19.00	2.50-3.75	0.060	0.030	0.20-0.40 N
S24100	Nitronic 32 (18-2 Mn)	0.15	11.00-14.00	1.00	16.50-19.50	0.50-2.50	0.060	0.030	0.20-0.40 N
S28200	18-18 Plus	0.15	17.0-19.0	1.00	17.5-19.5	. . .	0.045	0.030	0.5-1.5 Mo; 0.5-1.5 Cu; 0.4-0.6 N
S30310	303 Plus X (XM-5)	0.15	2.5-4.5	1.00	17.0-19.0	7.0-10.0	0.020	0.25 min	0.6 Mo
S30415	MVMA(c)	0.05	0.60	1.30	18.5	9.50	. . .	. . .	0.15 N; 0.04 Ce
S30424	304BI(d)	0.08	2.00	0.75	18.0-20.00	12.00-15.00	0.045	0.030	0.10 N; 1.00-1.25 B
S30452	304 HN (XM-21)	0.04-0.10	2.00	1.00	18.0-20.0	8.0-10.5	0.045	0.030	0.16-0.30 N
S30600	Cronifer 1815 LCSi	0.018	2.00	3.73-4.3	17.0-18.5	14.0-15.5	0.020	0.020	0.2 Mo
S30615	RA 85 H(c)	0.20	0.80	3.50	18.5	14.50	. . .	. . .	1.0 Al

S30815	253 MA	0.05-0.10	0.80	1.4-2.0	20.0-22.0	10.0-12.0	0.040	0.030	0.14-0.20 N; 0.03-0.08 Ce; 1.0 Al
S30940	Type 309 S Cb	0.08	2.00	1.00	22.0-24.0	12.0-15.0	0.045	0.030	10 × %C min to 1.10 max Nb
S31040	Type 310 Cb	0.08	2.00	1.50	24.0-26.0	19.0-22.0	0.045	0.030	10 × %C min to 1.10 max Nb + Ta
S31254	254 SMO	0.20	1.00	0.80	19.50-20.50	17.50-18.50	0.030	0.010	6.00-6.50 Mo; 0.50-1.00 Cu; 0.180-0.220 N
S31635	Type 316 Ti	0.08	2.00	1.00	16.0-18.0	10.0-14.0	0.045	0.030	5 × %(C + N) min to 0.70 max Ti; 2.0-3.0 Mo; 0.10 N
S31640	Type 316 Cb	0.08	2.00	1.00	16.0-18.0	10.0-14.0	0.045	0.030	10 × %C min to 1.10 max Nb + Ta; 2.0-3.0 Mo; 0.10 N
. . .	Type 316 HQ	0.030	2.00	1.00	16.00-18.25	10.00-14.00	0.030	0.015	3.00-4.00 Cu; 2.00-3.00 Mo
S31725	Type 317 LM	0.03	2.00	1.00	18.0-20.0	13.5-17.5	0.045	0.030	4.0-5.0 Mo; 0.10 N
S31726	17-14-4 LN	0.03	2.00	0.75	17.0-20.0	13.5-17.5	0.045	0.030	4.0-5.0 Mo; 0.10-0.20 N
S31753	Type 317 LN	0.03	2.00	1.00	18.0-21.0	11.0-15.0	0.030	0.030	0.10-0.22 N
S37000	Type 370	0.03-0.05	1.65-2.35	0.5-1.0	12.5-14.5	14.5-16.5	0.040	0.010	1.5-2.5 Mo; 0.1-0.4 Ti; 0.005 N; 0.05 Co
S38100	18-18-2 (XM-15)	0.08	2.00	1.5-2.5	17.0-19.0	17.5-18.5	0.030	0.030	. . .
S63008	21-4N	0.48-0.58	8.00-10.00	0.25	20.0-22.0	3.25-4.50	0.030	0.04-0.09	0.28-0.50 N
S63012	21-2N	0.50-0.60	7.0-9.50	0.25	19.25-21.50	1.50-2.75	0.050	0.04-0.09	0.20-0.40 N
S63017	21-12N	0.15-0.25	1.00-1.50	0.70-1.25	20.0-22.0	10.50-12.50	0.03	0.03	0.15-0.25 N
S63018	23-8N	0.28-0.38	1.50-3.50	0.60-0.90	22.0-24.0	7.0-9.0	0.04	0.015	0.28-0.35 N; 0.50 Co

S63198	19-9 DL	0.28-0.35	0.75-1.50	0.03-0.8	18.0-21.0	8.0-11.0	0.040	0.030	1.0-1.75 Mo; 0.1-0.35 Ti; 1.0-1.75 W; 0.25-0.60 Nb
N08020	20Cb-3	0.07	2.00	1.00	19.0-21.0	32.0-38.0	0.045	0.035	2.0-3.0 Mo; 3.0-4.0 Cu; 8 × %C min to 1.00 max Nb
N08024	20Mo-4	0.03	1.00	0.50	22.5-25.0	35.0-40.0	0.035	0.035	3.50-5.00 Mo; 0.50-1.50 Cu; 0.15-0.35 Nb
N08026	20Mo-6	0.03	1.00	0.50	22.0-26.00	33.0-37.20	0.03	0.03	5.00-6.70 Mo; 2.00-4.00 Cu
N08028	Sanicro 28	0.02	2.00	1.00	26.0-28.0	29.5-32.5	0.020	0.015	3.0-4.0 Mo; 0.6-1.4 Cu
N08366	AL-6X	0.035	2.00	1.00	20.0-22.0	23.5-25.5	0.030	0.030	6.0-7.0 Mo
N08367	AL-6XN	0.030	2.00	1.00	20.0-22.0	23.50-25.50	0.040	0.030	6.0-7.0 Mo; 0.18-0.25 N
N08700	JS-700	0.04	2.00	1.00	19.0-23.0	24.0-26.0	0.040	0.030	4.3-5.0 Mo; 8 × %C min to 0.5 max Nb; 0.5 Cu; 0.005 Pb; 0.035 S
N08800	Type 332	0.01	1.50	1.00	19.0-23.0	30.0-35.0	0.045	0.015	0.15-0.60 Ti; 0.15-0.60 Al
N08904	904L	0.02	2.00	1.00	19.0-23.0	23.0-28.0	0.045	0.035	4.0-5.0 Mo; 1.0-2.0 Cu
N08925	Cronifer 1925 hMo	0.02	1.00	0.50	24.0-26.0	19.0-21.0	0.045	0.030	6.0-7.0 Mo; 0.8-1.5 Cu; 0.10-0.20 N
. . .	Cronifer 2328	0.04	0.75	0.75	22.0-24.0	26.0-28.0	0.030	0.015	2.5-3.5 Cu; 0.4-0.7 Ti; 2.5-3.0 Mo

(a) Single values are maximum values unless otherwise indicated.

(b) Optional.

(c) Nominal compositions.

(d) UNS designation has not been specified; this designation appears in ASTM A 887 and merely indicates the form to be used.

Properties and Applications. The yield strengths of chromium-nickel austenitic stainless steels are rather modest and are comparable to those of mild steels. Typical minimum mechanical properties of annealed 300 series steels are yield strengths of 205 to 275 MPa (30 to 40 ksi), ultimate tensile strengths of 520 to 760 MPa (75 to 110 ksi), and elongations of 40 to 60%. Annealed 200 series alloys have higher yield strengths ranging from 345 to 480 MPa (50 to 70 ksi). Higher strengths are possible in cold-worked forms, especially in drawn wire, in which a tensile strength of 1200 MPa (175 ksi) or higher is possible. Figure 2 compares the work-hardening characteristics of 300 series and type 430 (ferritic) grades. The 200 series have work-hardening characteristics similar to types 301 and 302 in Fig. 2.

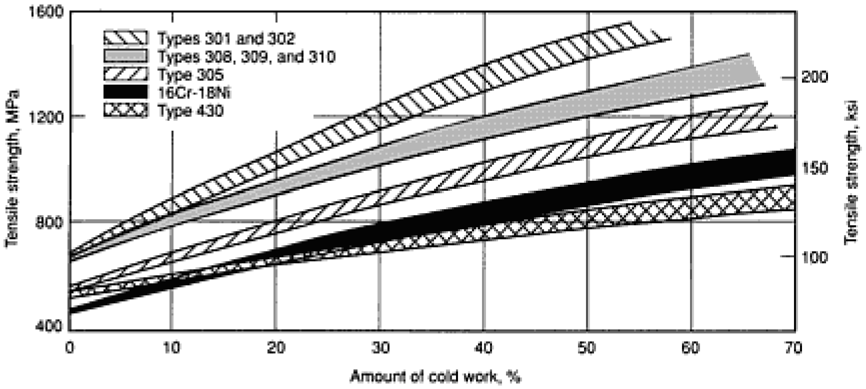

Fig. 2 Typical effect of cold rolling on the tensile strength of selected stainless steels

Even the leanest austenitic stainless steels (e.g., types 302 and 304) offer general corrosion resistance in the atmosphere, in many aqueous media, in the presence of foods, and in oxidizing acids such as nitric acid. Types 321 and 347 are essentially type 304 with additions of either titanium or niobium, respectively, which stabilize carbides against sensitization (see the subsection "Thermally Induced Embrittlement"). The addition of molybdenum in types 316/316L (Fig. 1) provides pitting resistance in phosphoric and acetic acids and dilute chloride solutions, as well as corrosion resistance in sulfurous acid. An even higher molybdenum content, as in type 316L (3%), and even richer alloys further enhance pitting resistance. Nitrogen is added to enhance strength at room temperature and, especially, at cryogenic temperatures (e.g., type 304N). Nitrogen is also added to reduce the rate of chromium carbide precipitation and, therefore, the susceptibility to sensitization. It is also added to molybdenum-containing alloys to increase resistance to chloride-induced pitting and crevice corrosion. Higher amounts of chromium and/or nickel are used to enhance high-temperature oxidation resistance (e.g., types 309, 310, and 330). Copper and nickel can be added to improve resistance to reducing acids, such as sulfuric acid (type 320). Some of the more corrosion-resistant alloys, such as N08020 (20Cb-3) have nickel contents high enough (32 to 37%) to rate UNS classification as nickel-base alloys. Alloys containing nickel, molybdenum (∼6%), and nitrogen (0.15 to 0.25%) are sometimes referred to as "superaustenitics," as shown in Fig. 1. These alloys were developed for improved resistance to chloride corrosion.

Duplex Stainless Steels

Characteristics and Compositions. Duplex stainless steels are two-phase alloys based on the Fe-Cr-Ni system. These materials typically comprise approximately equal proportions of ferrite and austenite phases in their microstructure and are characterized by their low carbon contents (<0.03%) and additions of molybdenum, nitrogen, tungsten, and copper. Typical chromium and nickel contents are 20 to 30% and 5 to 8%, respectively. Table 4 gives compositions of duplex stainless steels. The specific advantages offered by duplex stainless steels over conventional 300 series stainless steels are strength (approximately twice that of austenitic stainless steels), improved toughness and ductility (compared to ferritic grades), and superior chloride SCC resistance and pitting resistance.

Table 4 Chemical compositions of duplex stainless steels

UNS number(a)	Type/designation	Composition(b), %									
		C	**Mn**	**S**	**P**	**Si**	**Cr**	**Ni**	**Mo**	**N_2**	**Other**
S31200/. . .	44LN	0.03	2.00	0.03	0.045	1.00	24.0-26.0	5.5-6.5	1.2-2.0	0.14-0.20	. . .
S31260/39226	. . .	0.03	1.00	0.030	0.030	0.75	24.0-26.0	5.5-7.5	2.5-3.5	0.10-0.30	0.10-0.50 W, 0.20-0.80 Cu
S31500/39215	. . .	0.03	1.2-2.0	0.03	0.03	1.4-2.0	18.0-19.0	4.25-5.25	2.5-3.0	0.05-0.10	. . .
S31803/39209	UR45N	0.03	2.00	0.02	0.03	1.00	21.0-23.0	4.5-6.5	2.5-3.5	0.08-0.20	. . .
S32304/39230	2304	0.03	2.5	0.04	0.04	1.0	21.5-24.5	3.0-5.5	0.05-0.60	0.05-0.20	0.05-0.60 Cu
S32550/39255	. . .	0.03	1.5	0.03	0.04	1.0	24.0-27.0	4.5-6.5	2.9-3.9	0.10-0.25	1.5-2.5 Cu
S32750/39275	2507	0.03	1.2	0.02	0.035	1.0	24.0-26.0	6.0-8.0	3.0-5.0	0.24-0.32	0.5 Cu
S32760/39276	Zeron 100	0.03	1.0	0.01	0.03	1.0	24.0-26.0	6.0-8.0	3.0-4.0	0.30	0.5-1.0 Cu, 0.5-1.0 W
S32900/. . .	Type 329	0.06	1.00	0.03	0.04	0.75	23.0-28.0	2.5-5.0	1.0-2.0	(b)	. . .
S32950/39295	7 Mo Plus	0.03	2.00	0.01	0.035	0.60	26.0-29.0	3.5-5.2	1.0-2.5	0.15-0.35	. . .

(a) Certain UNS numbers for duplex grades have been replaced. For example, S32950/39295 means that the original UNS No. (S32950) has been replaced by S39295.

(b) Not specified

Properties and Applications. Duplex stainless steels are capable of tensile yield strengths ranging from 550 to 690 MPa (80 to 100 ksi). The high yield strength offers designers the use of thin-wall material (which can lead to major reductions in weight) with adequate pressure-containing and load-bearing capacity. The high alloy content and the presence of a ferritic matrix render duplex stainless steels susceptible to embrittlement and loss of mechanical strength, particularly toughness, through prolonged exposure to elevated temperatures. For this reason, the upper temperature of application is generally less than 300 °C (570 °F).

As with all stainless steels, composition also plays a major role in the corrosion resistance of duplex stainless steels. Pitting corrosion resistance is most easily affected. To determine the extent of pitting corrosion resistance offered by the material, the pitting resistance equivalent (PRE) is commonly used. The PRE is calculated by adding the weight percentages of elements that affect pitting corrosion resistance--namely, chromium, molybdenum, and nitrogen--and then normalizing them with respect to the effect of 1% Cr. The most commonly used formula for pitting resistance equivalent is:

$$\text{PRE} = \%\text{Cr} + 3.3(\%\text{Mo}) + 16(\%\text{N}) \qquad \textbf{(Eq 1)}$$

As indicated in the following table, the PRE values for duplex stainless steels range from approximately 24 for grades containing no molybdenum to greater than 40 for the more highly alloyed (Fe-25Cr-7Ni-3.5Mo-0.25N-W-Cu) grades:

UNS number	PRE range
S31200	30.2-35.8
S31260	33.9-42.4
S31500	27.1-30.5
S31803	30.5-37.8
S32304	22.5-29.7
S32550	35.2-43.9
S32750	37.7-47.6
S32760	40(min)
S32900	26.3-34.6

Duplex stainless steels have found widespread use in a range of industries, particularly the oil and gas, petrochemical, and pulp and paper industries. They are commonly used in aqueous, chloride-containing environments and as replacements for austenitic stainless steels that have suffered from either chloride SCC or pitting during service.

Precipitation-Hardening Stainless Steels

Characteristics and Compositions. Precipitation-hardenable (PH) stainless steels are chromium-nickel grades that can be hardened by an aging treatment. These grades are classified as austenitic (e.g., A-286), semiaustenitic (e.g., 17-7PH), or martensitic (e.g., 17-4PH). The classification is determined by their solution-annealed microstructure. The semiaustenitic alloys are subsequently heat treated so that the austenite transforms to martensite. Cold work is sometimes used to facilitate the aging reaction. Various alloying elements, such as aluminum, titanium, niobium, or copper, are used to achieve aging. Table 5 lists compositions of PH stainless steels.

Table 5 Chemical compositions of precipitation-hardening stainless steels

UNS No.	Alloy	Composition[(a)], %								
		C	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**P**	**S**	**Other**
Martensitic types										
S13800	PH13-8 Mo	0.05	0.10	0.10	12.25-13.25	7.5-8.5	2.0-2.5	0.01	0.008	0.90-1.35 Al; 0.01 N
S15500	15-5PH	0.07	1.00	1.00	14.0-15.5	3.5-5.5	. . .	0.04	0.03	2.5-4.5 Cu; 0.15-0.45 Nb
S17400	17-4PH	0.07	1.00	1.00	15.0-17.5	3.0-5.0	. . .	0.04	0.03	3.0-5.0 Cu; 0.15-0.45 Nb
S45000	Custom 450	0.05	1.00	1.00	14.0-16.0	5.0-7.0	0.5-1.0	0.03	0.03	1.25-1.75 Cu; 8 × %C min Nb
S45500	Custom 455	0.05	0.50	0.50	11.0-12.5	7.5-9.5	0.50	0.04	0.03	1.5-2.5 Cu; 0.8-1.4 Ti; 0.1-0.5 Nb
Semiaustenitic types										
S15700	PH15-7 Mo	0.09	1.00	1.00	14.0-16.0	6.50-7.75	2.0-3.0	0.04	0.04	0.75-1.50 Al
S17700	17-7PH	0.09	1.00	1.00	16.0-18.0	6.50-7.75	. . .	0.04	0.04	0.75-1.50 Al
S35000	AM-350	0.07-0.11	0.50-1.25	0.50	16.0-17.0	4.0-5.0	2.50-3.25	0.04	0.03	0.07-0.13 N
S35500	AM-355	0.10-0.15	0.50-1.25	0.50	15.0-16.0	4.0-5.0	2.50-3.25	0.04	0.03	0.07-0.13 N
Austenitic types										
S66286	A-286	0.08	2.00	1.00	13.5-16.0	24.0-27.0	1.0-1.5	0.025	0.025	1.90-2.35 Ti; 0.35 max Al; 0.10-0.50 V; 0.0030-0.0100 B
. . .	JBK-75[(b)]	0.015	0.05	0.02	14.5	29.5	1.25	0.006	0.002	2.15 Ti; 0.25 Al; 0.27 V; 0.0015 B

(a) Single values are maximum values unless otherwise indicated.

(b) Typical values

Properties and Applications. Like the hardenable 400 series martensitic stainless steels, PH alloys can attain high tensile yield strengths, up to 1700 MPa (250 ksi). Cold working prior to aging can result in even higher strengths. The PH grades generally have good ductility and toughness with moderate-to-good corrosion resistance. A better combination of strength and corrosion resistance is achieved than with the 400 series martensitic alloys. These improved properties are related to their higher chromium, nickel, and molybdenum contents, as well as their restricted carbon (0.040 max) levels. The low carbon content of the martensitic PH stainless steels is especially critical for toughness and good ductility. Because of their high strengths, most of the applications for PH stainless steels are in the aerospace and other high-technology industries.

Physical and Mechanical Properties of Stainless Steels

The physical properties of stainless steels are quite different from those of commonly used nonferrous alloys such as aluminum and copper alloys. However, when comparing the various stainless families with carbon steels, many similarities in properties exist, although there are some key differences. Like carbon steels, the density of stainless steels is ~8.0 g/cm^3, which is approximately three times greater than that of aluminum alloys (2.7 g/cm^3). Like carbon steels, stainless steels have a high modulus of elasticity (200 MPa, or 30 ksi) that is nearly twice that of copper alloys (115 MPa, or 17 ksi) and nearly three times that of aluminum alloys (70 MPa, or 10 ksi).

Differences among these materials are evident in thermal conductivity, thermal expansion, and electrical resistivity, as well. Figure 3 shows the large variation in thermal conductivity between various types of materials; 6061 aluminum alloy (Al-1Mg-0.6Si-0.3Cu-0.2Cr) has a very high thermal conductivity, followed by aluminum bronze (Cu-5Al), 1080 carbon steel, and then stainless steels. For stainless steels, alloying additions, especially nickel, copper, and chromium, greatly decrease thermal conductivity.

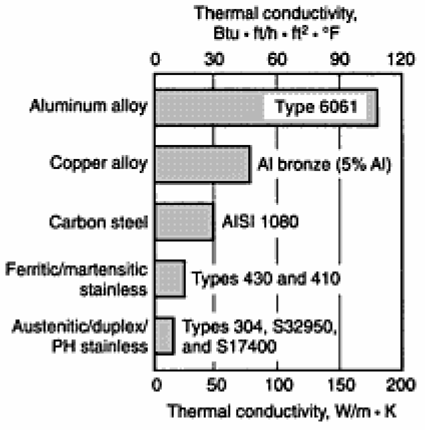

Fig. 3 Comparison of thermal conductivity for carbon steel, copper alloy, aluminum, and stainless steels

Thermal expansion (Fig. 4) is greatest for type 6061 aluminum alloy, followed by aluminum bronze and austenitic stainless alloys, and then ferritic and martensitic alloys. For austenitic stainless alloys, additions of nickel and copper can decrease thermal expansion. Stainless steels have high electrical resistivity (Fig. 5). Alloying additions tend to increase electrical resistivity. Therefore, the ferritic and martensitic stainless steels have lower electrical resistivity than the austenitic, duplex, and PH alloys, but higher electrical resistivity than 1080 carbon steel. Electrical resistivity of stainless steels is ~7.5 times greater than aluminum bronze and nearly 20 times greater than type 6061 aluminum alloy.

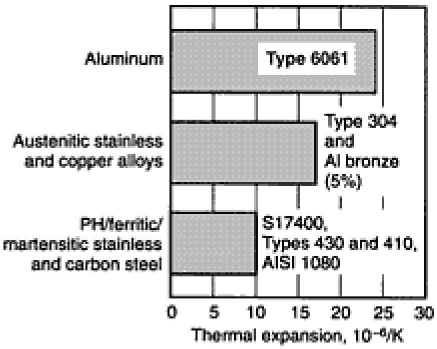

Fig. 4 Comparison of thermal expansion for carbon steel, copper alloy, aluminum, and stainless steels

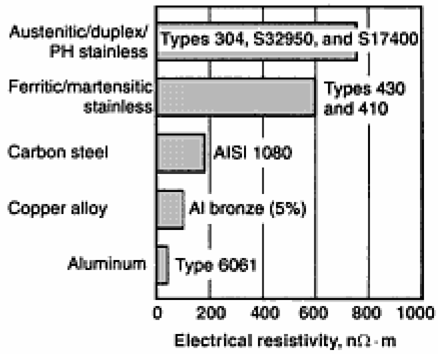

Fig. 5 Comparison of electrical resistivity for carbon steel, copper alloy, aluminum, and stainless steels

Mechanical Properties. Tables 6 and 7 list tensile properties and toughness for selected stainless alloys representing the five families. The grades listed under austenitic alloys have relatively low yield strength, compared with the heat-treatable alloys, but have the highest tensile ductility and toughness. The ferritic stainless steels (type 405 and 409) listed have tensile yield strengths similar to those of the austenitic grades but lower values for ultimate tensile strength, ductility, and toughness. The duplex stainless steels have twice the tensile yield strength of the austenitic and ferritic grades and approximately half the toughness. Again, their toughness is far superior to that of alloys that are heat treated and hardened.

Table 6 Minimum room-temperature mechanical properties for selected stainless steels

UNS No.	Common designation	Tensile strength		Yield strength[(a)]		Elongation, %	Reduction, in area, %	Hardness (max), HRB
		MPa	**ksi**	**MPa**	**ksi**			
Annealed austenitic stainless steels								
S30100	301	515	75	205	30	40	. . .	88
S30200	302	515	75	205	30	40	. . .	88
S30215	302B	515	75	205	30	. . .	. . .	. . .

S30430	302Cu	450-585	65-85	. . .	. . .	. . .	. . .	. . .
S30300	303	585(b)	85(b)	240(b)	35(b)	50(b)	55(b)	. . .
S30323	303Se	585(b)	85(b)	240(b)	35(b)	50(b)	55(b)	. . .
S30400	304	515	75	205	30	40	. . .	88
S30403	304L	480	70	170	25	40	. . .	88
S30451	304N	550	80	240	35	30	. . .	. . .
S31651	316N	550	80	240	35	30	. . .	. . .
S30500	305	480	70	170	25	40	. . .	88
S30800	308	515	75	205	30	40	. . .	88
S32100	321	515	75	205	30	40	. . .	88
S34700	347	515	75	205	30	40	. . .	88
S34800	348	515	75	205	30	40	. . .	88
S30900	309	515	75	205	30	40	. . .	95
S30908	309S	515	75	205	30	40	. . .	95
S31000	310	515	75	205	30	40	. . .	95
S31008	310S	515	75	205	30	40	. . .	95
S31400	314	515	75	205	30	30	40	. . .
S31600	316	515	75	205	30	40	. . .	95
S31620	316F	585(b)	85(b)	240(b)	35(b)	40(b)	55(b)	. . .
S31700	317	515	75	205	30	35	. . .	95
S31703	317L	515	75	205	30	35	. . .	95

N08330	330	480	70	210	30	30	. . .	. . .
S38400	384	415-550	60-80	. . .	. . .	. . .	. . .	. . .
S38500	385	415-550	60-80	. . .	. . .	. . .	. . .	. . .
N08904	904L	490	71	220	31	35	. . .	95
N08366	AL-6X	515	75	205	30	30	. . .	. . .
S38100	18-18-2	515	75	205	30	40	. . .	96
N08700	JS-700	550	80	205	30	30	40	. . .
N08020	20Cb-3	585	85	275	40	30	. . .	95
S30453	304LN	515	75	205	30	. . .	. . .	. . .
. . .	308L	550(b)	80(b)	207(b)	30(b)	60(b)	70(b)	. . .
. . .	312	655	95	. . .	. . .	20	. . .	. . .
S31653	316LN	515(b)	75(b)	205(b)	30(b)	60(b)	70(b)	. . .
S31725	317LM	515	75	205	30	35	50	95
N08800	332	550(b)	80(b)	240(b)	35(b)	45(b)	70(b)	. . .
N08700	JS-700	550	80	240	35	30	40	95
High-nitrogen austenitic stainless steels								
S20100	201	655	95	310	45	40	. . .	. . .
S20200	202	655	95	310	45	40	. . .	. . .
S20500	205	830(b)	120(b)	475(b)	69(b)	58(b)	62(b)	98(b)
S21600	216	690	100	415	60	40	. . .	100
S30451	304N	550	80	240	35	30	. . .	88

S30452	304HN	620	90	345	50	30	. . .	100
S31651	316N	550	80	240	35	30	. . .	95
S24100	Nitronic 32	690	100	380	55	30	50	. . .
S24000	Nitronic 33	690	100	415	60	40	. . .	. . .
S21900	Nitronic 40	690	100	415	60	40	. . .	. . .
S20910	Nitronic 50	825	120	515	75	30	. . .	. . .
S21800	Nitronic 60	655	95	345	50	35	55	. . .
S28200	18-18 Plus	760	110	415	60	35	55	. . .
S21400	Tenelon	860	125	485	70	40	. . .	. . .
Annealed ferritic stainless steels								
S40500	405	415	60	170	25	20	. . .	88
S40900	409	415	60	205	30	22(c)	. . .	80
S42900	429	450	65	205	30	22(c)	. . .	88
S43000	430	450	65	205	30	22(c)	. . .	88
S43020	430F	585-860	85-125	. . .	. . .	. . .	. . .	. . .
S43400	434	530(b)	77(b)	365(b)	53(b)	23(b)	. . .	83
S43600	436	530(b)	77(b)	365(b)	53(b)	23(b)	. . .	83
S44200	442	515	75	275	40	20	. . .	95
S44400	444	415	60	275	40	20	. . .	95
S44600	446	515	75	275	40	20	. . .	95
S44625	E-Brite 26-1	450	65	275	40	22(c)	. . .	90

S44660	Sea-cure/SC-1	550	80	380	55	20	. . .	100
S44700	29-4	550	80	415	60	20	. . .	88
S44800	29-4-2	550	80	415	60	20	. . .	98
. . .	18SR	620(b)	90(c)	450(c)	65(c)	25(e)	. . .	90 min(b)
Annealed duplex stainless steels								
S31200	44LN	690	100	450	65	25	. . .	. . .
S31500	. . .	630	92	440	64	30	. . .	30.5 HRC(b)
S31803	UR45N	620	90	450	65	25	. . .	30.5 HRC(b)
S32304	2304	600	87	400	58	25	. . .	30.5 HRC(b)
S32550	. . .	760	110	550	80	15	. . .	31.5 HRC(b)
S32750	2507	800	116	550	80	15	. . .	32 HRC(b)
S32760	Zeron 100	750	109	550	80	25	. . .	. . .
S32900	Type 329	620	90	485	70	20	. . .	28 HRC(b)
S32950	7 Mo Plus	690	100	480	70	20	. . .	30.5 HRC(b)
Martensitic stainless steels								
S40300	403	485	70	205	30	25(c)	. . .	88
S41000	410	450	65	205	30	22(c)	. . .	95
S41008	410S	415	60	205	30	22	. . .	95
S41040	410Cb	485	70	275	40	12	35	. . .
S41400	414	795	115	620	90	15	45	. . .
S41800	418(d)	1450(b)	210(b)	1210(b)	175(b)	18(b)	52(b)	. . .

S42000	420(e)	1720	250	1480(b)	215(b)	8(b)	25(b)	52 HRC(b)
S42200	422(f)	965	140	760	110	13	30	. . .
S43100	431(d)	1370(b)	198(d)	1030(b)	149(b)	16(b)	55(b)	. . .
S44002	440A	725(b)	105(d)	415(b)	60(b)	20(b)	. . .	95
S44003	440B	740(b)	107(d)	425(b)	62(b)	18(b)	. . .	96
S44004	440C	760(b)	110(d)	450(b)	65(b)	14(b)	. . .	97
. . .	414L	795(b)	115(d)	550(b)	80(b)	20(b)	60(b)	. . .
S41610	416 Plus X	515(b)	75	275(b)	40(b)	30(b)	60(b)	. . .
Precipitation-hardening stainless steels								
S13800	PH13-8Mo(g)	1520	220	1410	205	6-10	. . .	45 HRC (min)
S15500	15-5PH(h)	1310	190	1170	170		. . .	
S17400	17-4PH(h)	1310	190	1170	170	5-10	. . .	40 HRC (min)
S45000	Custom 450(h)	1240	180	1170	170	3-5	. . .	40 HRC (min)
S45500	Custom 455(g)	1530	222	1410	205	≤ 4	. . .	44 HRC (min)
S15700	PH15-7Mo(h)	1650	240	1590	230	1	. . .	46 HRC (min)
S17700	17-7PH(g)	1450	210	1310	190	1-6	. . .	43 HRC (min)
S35000	AM-350(i)	1140	165	1000	145	2-8	. . .	36 HRC (min)
S35500	AM-355(i)	1170	170	1030	150	12	. . .	37 HRC (min)
S66286	A-286(j)	896-965	125-140	655	95	4-15	. . .	24 HRC (min)

(a) At 0.2% offset.

(b) Typical values.

(c) 20% elongation for thicknesses of 1.3 mm (0.050 in.) or less.

(d) Tempered at 260 °C (500 °F).

(e) Tempered at 205 °C (400 °F).

(f) Intermediate and hard tempers.

(g) Aged at 510 °C (950 °F).

(h) Aged at 480 °C (900 °F).

(i) Aged at 535 °C (1000 °F).

(j) Aged at 730 °C (1350 °F)

Table 7 Tensile and impact properties of selected stainless steels

UNS or AISI type	Condition	Rockwell hardness	Average tensile properties						Charpy V-notch impact strength	
			Yield strength, 0.2% offset		**Ultimate tensile strength**		**Elongation in 50.8 mm (2.0 in.), %**	**Reduction of area, %**		
			MPa	**ksi**	**MPa**	**ksi**			**J**	**ft · lbf**
Austenitic stainless										
Type 304	Annealed	81 HRB	241	35	586	85	60.0	70.0	≥ 325	≥ 240
N08020	Annealed	84 HRB	276	40	621	90	50.0	65.0	271	200
S20161	Annealed	93 HRB	365	53	970	140	59.0	64.0	≥ 325	≥ 240
S21800	Annealed	95 HRB	414	60	710	103	64.0	74.0	≥ 325	≥ 240
Ferritic										

Type 430	Annealed	82 HRB	310	45	517	75	30.0	65.0	217	161
Duplex										
S32950	Annealed	100 HRB	570	82	760	110	38.0	78.0	157	116
Martensitic										
Type 410	Oil quenched from 1010 °C (1850 °F) and tempered:									
	at 250 °C (500 °F)	43 HRC	1089	158	1337	193	17.0	62.0	76	56
	at 593 °C (1100 °F)	26 HRC	724	105	827	120	20.0	63.0	52	38
Type 420	Oil quenched from 1038 °C (1900 °F) and tempered at 316 °C (600 °F)	52 HRC	1482	215	1724	250	8.0	25.0	20	15
Type 440C	Oil quenched from 1038 °C (1900 °F) and tempered at 316 °C (600 °F)	57 HRC	1896	275	1975	285	2.0	10.0	2	3
Precipitation hardened										
S45500	Water quenched from 1038 °C (1900 °F) and aged:									
	at 482 °C (900 °F)	49 HRC	1620	235	1689	245	10.0	45.0	12	9
	at 566 °C (1050 °F)	40 HRC	1207	175	1310	190	15.0	55.0	47	35
S17400	Water quenched from 1038 °C (1900 °F) and aged:									
	at 482 °C (900 °F)	44 HRC	1262	183	1365	198	15.0	52.0	21	16
	at 621 °C (1150 °F)	33 HRC	869	126	1131	164	17.0	59.0	75	55

The martensitic alloys listed in Tables 6 and 7 have a large variation in strength, ductility, and toughness. In the annealed condition, their properties are similar to those of the ferritic alloys, with strength increasing and ductility decreasing with increasing carbon content. The higher carbon-containing alloys, type 420 and type 440C, are generally tempered at a low temperature (330 °C, or 625 °F max) to maximize their strength. Conversely, type 410 is tempered over a wide temperature range, from 260 to 650 °C (500 to 1200 °F).

The PH alloys, such as the martensitic grades S45500 and S17400, have higher annealed strength and lower ductility than the 400 series martensitic alloys and are aged at temperatures ranging from 480 to 620 °C (895 to 1150 °F). Their strength is dependent on the hardener (titanium, niobium, and copper), the amount of hardener, and the aging temperatures used. Toughness is either similar or superior to the 400 series martensitic alloys at a given strength level.

Factors in Selection

The selection of stainless steels can be based on corrosion resistance, fabrication characteristics, availability, mechanical properties in specific temperature ranges, and product cost. However, corrosion resistance and mechanical properties are usually the most important factors in selecting a grade for a given application.

Characteristics to be considered in selecting the proper type of stainless steel for a specific application include:

- Corrosion resistance
- Resistance to oxidation and sulfidation
- Strength and ductility at ambient and service temperatures
- Suitability for intended fabrication techniques
- Suitability for intended cleaning procedures
- Stability of properties in service
- Toughness
- Resistance to abrasion, erosion, galling, and seizing
- Surface finish and/or reflectivity
- Physical property characteristics, such as magnetic properties, thermal conductivity, and electrical resistivity
- Sharpness, or retention of cutting edge
- Rigidity
- Dimensional stability

Corrosion resistance is frequently the most important characteristic of a stainless steel but often is also the most difficult to assess for a specific application. General corrosion resistance to pure chemical solutions is comparatively easy to determine, but actual environments are usually much more complex.

General corrosion is often much less serious than localized forms such as SCC, crevice corrosion in tight spaces or under deposits, pitting attack, and intergranular attack in sensitized material such as weld heat-affected zones. Such localized corrosion can cause unexpected and sometimes catastrophic failure while most of the structure remains unaffected, and therefore it must be considered carefully in the design and selection of the proper grade of stainless steel. Corrosive attack can also be increased dramatically by seemingly minor impurities in the medium that may be difficult to anticipate but that can have major effects, even when present in only parts-per-million concentrations: heat transfer through the steel to or from the corrosive medium, contact with dissimilar metallic materials, stray electrical currents, and many other subtle factors. At elevated temperatures, attack can be accelerated significantly by seemingly minor changes in atmosphere that affect scaling, sulfidation, or carburization.

Despite these complications, a suitable steel can be selected for most applications on the basis of experience, perhaps with assistance from the steel producer. Laboratory corrosion data can be misleading in predicting service performance. Even actual service data have limitations, because similar corrosive media may differ substantially because of slight variations in some of the corrosion conditions listed previously. For difficult applications, extensive study of comparative data may be necessary, sometimes followed by pilot plant or in-service testing. Other important factors that must be considered when selecting a stainless steel for a corrosion application include:

- Chemical composition of the corrosive medium, including impurities
- Physical state of the medium: liquid, gaseous, solid, or combinations thereof
- Temperature
- Temperature variations
- Aeration of the medium

- Oxygen content of the medium
- Bacteria content of the medium
- Ionization of the medium
- Repeated formation and collapse of bubbles in the medium
- Relative motion of the medium with respect to the steel
- Chemical composition of the metal
- Nature and distribution of microstructural constituents
- Continuity of exposure of the metal to the medium
- Surface condition of the metal
- Stresses in the metal during exposure to the medium
- Contact of the metal with one or more dissimilar metallic materials
- Stray electrical currents
- Differences in electric potential
- Marine growth such as barnacles
- Sludge deposits on the metal
- Carbon deposits from heated organic compounds
- Dust on exposed surfaces
- Effects of welding, brazing, and soldering

More detailed information on selection of stainless steels for use in various corrosive environments can be found in the article "Corrosion of Wrought Stainless Steels" in this Section.

Mechanical properties at service temperature are obviously important, but satisfactory performance at other temperatures must also be considered. Thus, a product for arctic service must have suitable properties at subzero temperatures even though steady-state operating temperatures may be much higher; room-temperature properties after extended service at elevated temperature can be important for applications such as boilers and jet engines, which are intermittently shut down.

Wear and Galling Resistance. Stainless steels are characterized as having relatively poor wear and galling resistance, but they are often required for a particular application because of their corrosion resistance. Therefore, finding the most effective alloy to withstand wear and galling can be a difficult problem for design engineers. Lubricants and coatings are often used to reduce wear, although lubricant use is precluded in many applications, such as high-temperature environments, in which they can break down, or food and pharmaceutical processing equipment, which require sanitation. Additionally, a critical part, such as a valve in a power plant, must resist galling or seizing, because it can shut down or endanger the entire plant. Tables 8 and 9 present a comparison of wear compatibility and galling resistance of selected stainless steels.

Table 8 Wear compatibility of dissimilar-mated stainless steels

Alloy	Volume loss, mm^3						
	Type 304 (99 HRB)	**Type 316 (91 HRB)**	**S17400 (43 HRC)**	**S24100 (95 HRB)**	**S20910 (99 HRB)**	**S21800 (95 HRB)**	**Type 440C (57 HRC)**
Type 304	16.4	. . .	. . .	. . .	. . .	. . .	. . .
Type 316	13.5	16.4	. . .	. . .	. . .	. . .	. . .
S17400	31.7	23.7	67.7	. . .	. . .	. . .	. . .

S24100	10.8	12.1	22.1	9.5	. . .	. . .	. . .
S20910	11.5	12.2	20.1	10.6	12.8	. . .	. . .
S21800	7.7	5.5	6.9	4.1	4.5	3.6	. . .
Type 440C	5.3	5.0	14.6	4.0	5.5	3.1	4.9

Based on crossed-cylinder wear test, ASTM G 83, 105 revolutions/min test speed, 10,000 cycles, 71 N (16 lbf); (weight loss/1000 cycles converted to total volume loss)

Table 9 Threshold galling stress for selected stainless steels

Alloy	Condition and nominal Rockwell hardness	Type 410		Type 416		Type 430		Type 440C		Type 303		Type 304		Type 316		S17400		S24100		S21800	
		MPa	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**
Type 410	Tempered (38 HRC)	21	3	28	4	21	3	21	3	28	4	14	2	14	2	21	3	317	46	345(a)	50
Type 416	Tempered (36 HRC)	28	4	90	13	21	3	145	21	62	9	165	24	290	42	14	2	310	45	345(a)	50
Type 430	Annealed (84 HRB)	21	3	21	3	14	2	14	2	14	2	14	2	14	2	21	3	55	8	248	36
Type 440C	Tempered (56 HRC)	21	3	145	21	14	2	76	11	34	5	21	3	255	37	21	3	345(a)	50	345(a)	50
Type 303	Annealed (82 HRB)	28	4	62	9	14	2	34	5	14	2	14	2	21	3	21	3	345(a)	50	345(a)	50
Type 304	Annealed (77 HRB)	14	2	165	24	14	2	21	3	14	2	14	2	14	2	14	2	207	30	345(a)	50
Type 316	Annealed (81 HRB)	14	2	290	42	14	2	255	37	21	3	14	2	14	2	14	2	21	3	262	38
S17400	Aged (84 HRB)	21	3	14	2	21	3	21	3	14	2	14	2	14	2	14	2	345(a)	50	345(a)	50
S21800	Annealed (94 HRB)	345(a)	50	345(a)	50	248	36	345(a)	50	345(a)	50	345(a)	50	262	38	345(a)	50	345(a)	50	345(a)	50

Based on button-on-block test, ASTM G 98, unlubricated ground finish; condition and hardness apply to both horizontal and vertical axes.

(a) Did not gall

Fabrication and Cleaning. Frequently a particular stainless steel is chosen for a fabrication characteristic such as machinability, formability, or weldability. Even a required or preferred cleaning procedure can dictate the selection of a specific type. For instance, a weldment that is to be cleaned in a medium such as nitric-hydrofluoric acid, which attacks sensitized stainless steel, should be produced from stabilized or low-carbon stainless steel even though sensitization may not affect performance under service conditions.

Surface Finish. Other characteristics in the stainless steel selection checklist are vital for some specialized applications but are of little concern for others. Among these characteristics, surface finish is important more often than any other except corrosion resistance. Stainless steels are sometimes selected because they are available in a variety of attractive finishes. Surface finish selection can be made on the basis of appearance, frictional characteristics, or sanitation. The effect of finish on sanitation sometimes is thought to be simpler than it actually is, and tests of several candidate finishes may be advisable. The selection of finish can in turn influence the selection of the alloy because of differences in availability or durability of the various finishes for different types.

Product Forms

Plate is a flat-rolled or forged product more than 254 mm (10 in.) in width and at least 4.76 mm (0.1875 in.) in thickness. Stainless steel plate generally is produced in the annealed condition and is either blast cleaned or pickled. Blast cleaning generally is followed by further cleaning in appropriate acids to remove surface contaminants such as particles of steel picked up from the mill rolls.

Sheet is a flat-rolled product in coils or cut lengths at least 610 mm (24 in.) wide and less than 4.76 mm (0.1875 in.) thick. Stainless steel sheet is produced in nearly all types except the free-machining and certain martensitic grades.

Strip is a flat-rolled product, in coils or cut lengths, less than 610 mm (24 in.) wide and 0.13 to 4.76 mm (0.005 to 0.1875 in.) thick. Cold finished material 0.13 mm (0.005 in.) thick and less than 610 mm (24 in.) wide fits the definitions of both strip and foil and can be referred to using either term.

Cold rolled stainless steel strip is manufactured from hot rolled, annealed, and pickled strip (or from slit sheet) by rolling between polished rolls. Depending on desired thickness, various numbers of cold rolling passes through the mill are required for effecting the necessary reduction and for securing the desired surface characteristics and mechanical properties.

Hot rolled stainless steel strip is a semifinished product obtained by hot rolling slabs or billets and is produced for conversion to finished strip by cold rolling.

Foil is a flat-rolled product, in coil form, up to 0.13 mm (0.005 in.) thick and less than 610 mm (24 in.) wide. Foil is produced in slit widths with edge conditions corresponding to No. 3 (as-slit) and No. 5 (square edge produced by rolling or filing after slitting) edge conditions for strip.

Bar is a product supplied in straight lengths; it is either hot or cold finished and is available in various shapes, sizes, and surface finishes. This category includes small shapes, whose dimensions do not exceed 127 mm (5 in.), and hot-rolled flat stock at least 3.2 mm (0.125 in.) thick and up to 254 mm (10 in.) wide.

Hot finished bar commonly is produced by hot rolling, forging, or pressing ingots to blooms or billets of intermediate size, which are subsequently hot rolled, forged, or extruded to final dimensions. Whether rolling, forging, or extrusion is selected as the finishing method depends on several factors, including composition and final size.

Cold-finished bar is produced from hot-finished bar or rod by additional operations such as cold rolling or cold drawing, which result in the close control of dimensions, a smooth surface finish, and higher tensile and yield strengths. Sizes and shapes of cold-reduced stock classified as bar are essentially the same as for hot-finished bar, except that all cold-reduced flat stock less than 4.76 mm (0.1875 in.) thick and over 9.5 mm (0.375 in.) wide is classified as strip.

Wire is a coiled product derived by cold finishing hot rolled and annealed rod. Cold finishing imparts excellent dimensional accuracy, good surface smoothness, fine finish, and specific mechanical properties. Wire is produced in several tempers and finishes.

Wire is customarily referred to as round wire when the contour is completely cylindrical and as shape wire when the contour is other than cylindrical. Shape wire is cold finished either by drawing or by a combination of drawing and rolling.

Special Wire Commodities. There are many classes of stainless steel wire that have been developed for specific components or for particular applications. The unique properties of each of these individual wire commodities are developed by employing a particular combination of composition, steel quality, process heat treatment, and cold-drawing practice.

Cold heading wire is produced in any of the various types of stainless steel. In all instances, cold heading wire is subjected to special testing and inspection to ensure satisfactory performance in cold heading and cold forging operations.

Of the chromium-nickel group, types 305 and 302Cu are used for cold heading wire and generally are necessary for severe upsetting. Other grades commonly cold formed include 303Se, 304, 316, 321, 347, 384, 410, 420, 430, and 431.

Spring wire is drawn from annealed rod. The types of stainless steel in which spring wire is commonly produced include 302, 304, 316, and 20Cb-3 (N08020).

Spring wire in large sizes can be furnished in a variety of finishes such as dry-drawn lead, copper, lime and soap, or oxide and soap. Fine sizes usually are wet drawn, although they can be dry drawn.

Rope wire is used to make rope, cable, and cord for a variety of uses such as aircraft control cables, marine ropes, elevator cables, slings, and anchor cables.

Rope wire is made of type 302 or 304 unless a higher level of corrosion resistance is required, in which case type 316 is generally selected. Special nonmagnetic characteristics may be required, which necessitates selection of heats having little or no ferrite or martensite in the microstructure and use of special drawing practices to limit or avoid deformation-induced transformation to martensite.

Weaving wire is used in weaving of screens for many different applications in coal mines, sand-and-gravel pits, paper mills, chemical plants, dairy plants, oil refineries, and food-processing plants. Annealing and final drawing must be carefully controlled to maintain uniform temper and finish throughout each coil or spool. Because weaving wire must be ductile, it usually is furnished in the annealed temper with a bright annealed finish or in the soft temper with either a lime-soap finish or an oil- or grease-drawn finish. Most types of stainless steels are available as weaving wire.

Stainless welding wire is available for many grades to provide good weldability with optimized mechanical properties and corrosion resistance of the weldment. Stainless steel weld wire is produced in layer-level wound spools, straight lengths (both included in the American Welding Society AWS A5.9), and coated electrodes (AWS A5.4).

Semifinished Products. Blooms, billets, and slabs are hot rolled, hot forged, or hot pressed to approximate cross-sectional dimensions and generally have rounded corners. Round billets are also produced, typically for extrusion or closed-die forging. These semifinished products, as well as tube rounds, are produced in random lengths or are cut to specified lengths or to specified weights. There are no invariable criteria for distinguishing between the terms bloom and billet, and often they are used interchangeably.

The nominal cross-sectional dimensions of blooms, billets, and slabs are designated in inches and fractions of an inch. The size ranges commonly listed as hot-rolled stainless steel blooms, billets, and slabs include square sections 100 × 100 mm (4 × 4 in.) and larger, and rectangular sections at least 10,300 mm^2 (16 in.^{2}) in cross-sectional area.

Pipe, tubes, and tubing are made either by piercing rounds or by rolling and welding strip. They are used for conveying gases, liquids, and solids and for diverse mechanical and structural purposes. (Cylindrical forms intended for use as containers for storage and shipping purposes, and products cast to tubular shape, are not included in this category.)

Pipe is distinguished from tubes chiefly by the fact that it is commonly produced in relatively few standard sizes. Tubing is generally made to more exacting specifications regarding dimensions, finish, chemical composition, and mechanical properties than either pipe or tubes.

Stainless steel tubular products are classified as follows according to intended service:

- Stainless steel tubing for general corrosion-resistant service
- Stainless steel pressure pipe
- Seamless steel pressure tubes
- Stainless steel sanitary tubing
- Stainless steel mechanical tubing
- Stainless steel aircraft tubing
- Aircraft structural tubing
- Aircraft hydraulic-line tubing

Notch Toughness and Transition Temperature

Notched-bar impact testing of stainless steels is likely to show a wide scatter in test results, regardless of type or test conditions. Because of this wide scatter, only general behavior of the different classes can be described.

Austenitic types have good notched-bar impact resistance. Charpy impact energies of 150 J (110 ft · lbf) or greater are typical of all austenitic types at room temperature (Table 7). Cryogenic temperatures have little or no effect on notch toughness; ordinarily, austenitic stainless steels maintain values exceeding 130 J (95 ft · lbf), even at very low temperatures (Table 10). Conversely, cold work lowers the resistance to impact at all temperatures.

Table 10 Typical cryogenic properties of selected annealed austenitic stainless steels

Alloy	Temperature		0.2% yield strength		Ultimate tensile strength		Elongation in 4D, %	Reduction of area, %	Charpy V-notch strength	
	°C	**°F**	**MPa**	**ksi**	**MPa**	**ksi**			**J**	**ft · lbf**
Type 305	23	74	234	34	545	79	77	82	325	240
	-73	-100	324	47	876	127	82	79	294	217
	-196	-320	365	53	1358	197	66	69	237	175
Type 384	23	74	214	31	503	73	63	82	325	240
	-73	-100	303	44	683	99	97	79	316	233
	-196	-320	421	61	1027	149	90	77	225	166
S21904 (21-6-9)	24	75	359	52	696	101	53	73	325	240
	-79	-110	607	88	1007	146	52	72	289	213
	-196	-320	972	141	1510	219	35	34	129	95
S28200 (18-18 Plus)	24	75	476	69	827	120	65	75	325	240

	-73	-100	648	94	1138	165	64	74	285	210
	-196	-320	1000	145	1641	238	16	30	38	28

Martensitic and ferritic stainless steels exhibit a decreasing resistance to impact with decreasing temperature, and the fracture appearance changes from a ductile mode at mildly elevated temperatures to a brittle mode at low temperatures. This fracture transition is characteristic of martensitic and ferritic materials. Both the upper-shelf energy and the lower-shelf energy are not greatly influenced by heat treatment in these stainless steels. However, the temperature range over which transition occurs is affected by heat treatment, minor variations in composition, and cold work. Heat treatments that result in high hardness move the transition range to higher temperatures, and those that result in low hardness move the transition range to lower temperatures.

Fracture Toughness

Fracture toughness data are not available for many of the standard types of stainless steels. Most of the testing has been concentrated on the high-strength martensitic PH stainless steels because these materials have been used in critical applications where fracture-toughness testing has been found most useful for evaluating materials. Although K_{Ic} values are dependent on the testing conditions, specimen orientation, and condition (heat treatment) of the material, studies have shown that average K_{Ic} values for martensitic PH steels range from approximately 50 MPa$\sqrt{\text{m}}$ (45 ksi$\sqrt{\text{in.}}$) to 120 MPa$\sqrt{\text{m}}$ (110 ksi$\sqrt{\text{in.}}$).

Fracture toughness data for austenitic stainless steels are limited because of the high ductility and high toughness of these grades. The fracture toughness data that are available were obtained by the J-integral method (J_c initial toughness values) and are given in units of kJ/m^2. Extensive fracture toughness testing of types 304 and 316 stainless steels shows that they are extremely resistant to fracture. Both types exhibit a ductile fracture response under a wide variety of conditions, but J_c values are highly variable, typically ranging from 169 to 1660 kJ/m^2 at room temperature and from 130 to 1420 kJ/m^2 at approximately 400 °C (750 °F).

Fatigue Properties

Fatigue crack initiation tests are procedures in which a specimen or part is subjected to cyclic loading to failure. A large portion of the total number of cycles in these tests is spent initiating the crack. Although crack initiation tests conducted on small specimens do not precisely establish the fatigue life of a large part, such tests do provide data on the intrinsic fatigue crack initiation behavior of a stainless steel. As a result, such data can be used to develop criteria to prevent fatigue failures in engineering design. Examples of the use of small-specimen fatigue test data can be found in the basis of the fatigue design codes for boilers and pressure vessels, complex welded, riveted, or bolted structures, and automotive and aerospace components. Factors influencing the fatigue life of stainless steels include temperature, specimen orientation (e.g., longitudinal versus transverse), heat treatment (e.g., annealed versus quench hardened), hardness, and surface condition (Fig. 6).

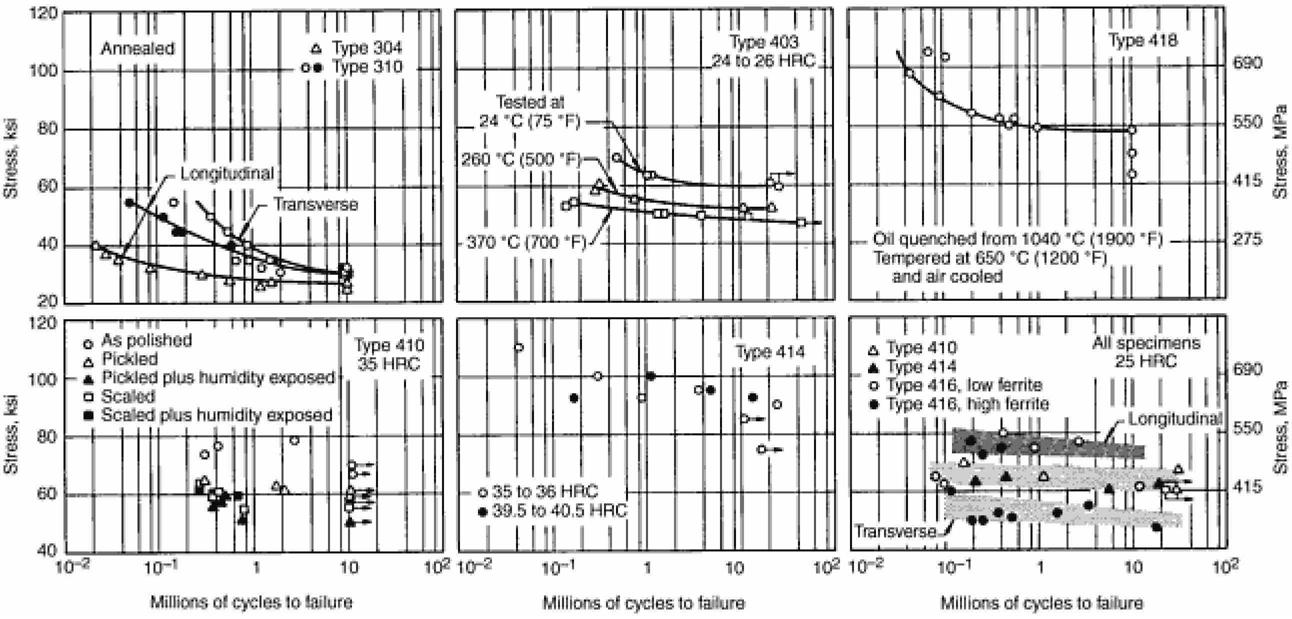

Fig. 6 Factors affecting fatigue properties of stainless steels

Three types of fatigue tests are used to develop data on fatigue behavior of stainless steels. The most common of these tests is the rotating-beam test, which most closely approximates the kind of loading to which shafts and axles are subjected. The flexural fatigue test is used to evaluate the behavior of sheet and most closely simulates the action of leaf springs, which are expected to flex without deforming or breaking. The axial-load fatigue test subjects a fatigue specimen to unidirectional loading that can range from full reversal (tension-compression) to tension-tension loading, and can have virtually any conceivable ratio of maximum stress to minimum stress. In general, fatigue conditions involving tension-compression loading (stress ratio, *R*, between 0 and -1) lead to shorter fatigue lives than conditions involving tension-tension loading (stress ratio, *R*, between 0 and +1) at the same value of maximum stress.

Fatigue crack growth (FCG) rates of austenitic stainless steels have been extensively studied, given their widespread use in high-temperature structural parts with cyclic stressing over a wide range of frequencies, temperatures, environments, and load ratios. Results of FCG tests have been analyzed on the basis of fracture mechanics concepts, leading to a well-documented collection of fatigue crack growth rate data for the austenitic stainless steels--particularly types 304 and 316. Data are also available on duplex grades; martensitic grades; and martensitic, semi-austenitic, and austenitic PH stainless steels. Figure 7 shows the effects of condition (annealed versus cold worked) and temperature on the FCG rates of type 304 stainless steel. This figure shows that the high-ΔK crack growth rates were lower for the cold-worked specimens than for the annealed specimens. Crack growth rates were higher for the specimens tested at 427 °C (800 °F) than for corresponding specimens tested at room temperature.

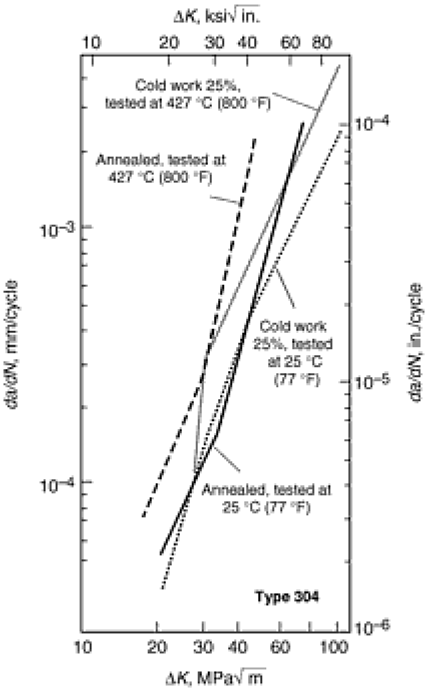

Fig. 7 Fatigue crack growth rates for annealed and cold worked type 304 stainless steel at 25 and 427 °C (77 and 800 °F), 0.17 Hz, and an *R* ratio of 0

Elevated-Temperature Mechanical Properties

Many stainless steels--particularly the austenitic types 304, 309, 310, 316, 321, 330, and 347; certain precipitation-hardening types such as PH 15-7 Mo, 15-5 PH, 17-4 PH, 17-7 PH, AM-350 and AM-355; and certain martensitic types such as the so-called "Super 12 Chrome" steels that contain molybdenum (up to 3%), tungsten (up to 3.5%), and/or vanadium--are used extensively for elevated-temperature applications. As shown in Fig. 8, the austenitic types retain their strength at higher temperatures (up to 815 °C, or 1500 °F) than do the other types of stainless steels. For the best creep strength and creep-rupture strength, the H grades of austenitic stainless steels are specified. These steels have carbon contents of 0.04 to 0.10% (Table 3) and are solution annealed at temperatures high enough to produce improved creep properties.

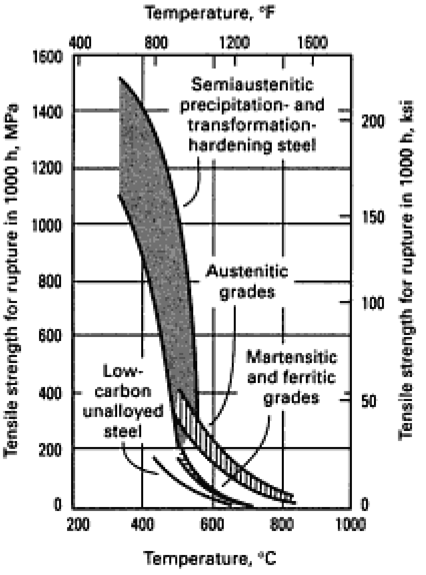

Fig. 8 General comparison of the hot-strength characteristics of austenitic, martensitic, and ferritic stainless steels with those of low-carbon unalloyed steel and semiaustenitic precipitation- and transformation-hardening steels

Valve steels are austenitic nitrogen-strengthened steels that have been used extensively in automotive/internal combustion engine valve applications. Examples of such alloys include 21-2N (21Cr, 8Mn, 2Ni + N), 21-4N (21Cr, 9Mn, 4Ni + N), 21-12N (21Cr, 12Ni, 1.25Mn + N), and 23-8N (21Cr, 8Ni, 3.5Mn + N) (see Table 3). The nitrogen contents in these alloys range from 0.20 to 0.50%. These engine valve grades are used at temperatures up to 760 °C (1400 °F), but they provide fairly low strength at the upper end of their temperature capability.

As described in the section "Thermally Induced Embrittlement," extended service at elevated temperature can result in embrittlement (sensitization) of austenitic stainless steels, which degrades the ability of the material to withstand corrosion and induces embrittlement. Most often, such degradation is caused by the precipitation of secondary phases such as carbides and sigma phase. Precipitation depends on both time and temperature: longer times at temperature and higher temperatures both promote more extensive precipitation.

Thermally Induced Embrittlement

Stainless steels are susceptible to embrittlement during thermal treatment or elevated-temperature service. These thermally induced forms of embrittlement of stainless steels include sensitization, 475 °C (885 °F) embrittlement, and σ-phase embrittlement.

Sensitization

Stainless steels become susceptible to localized intergranular corrosion when chromium carbides form at the grain boundaries during high-temperature exposure. This depletion of chromium at the grain boundaries is termed "sensitization" because the alloys become more sensitive to localized attack in corrosive environments.

Austenitic Stainless Steels. At temperatures above approximately 1035 °C (1900 °F), chromium carbides are completely dissolved in austenitic stainless steels. However, when these steels are slowly cooled from these high temperatures or reheated into the range of 425 to 815 °C (800 to 1500 °F), chromium carbides are precipitated at the grain boundaries. These carbides contain more chromium than the matrix contains.

The precipitation of the carbides depletes the matrix of chromium adjacent to the grain boundary. The diffusion rate of chromium in austenite is slow at the precipitation temperatures; therefore, the depleted zone persists, and the alloy is sensitized to intergranular corrosion. This sensitization occurs because the depleted zones have higher corrosion rates than the matrix in many environments. Loss of toughness also results from sensitization.

If the austenitic stainless steels are cooled rapidly to below approximately 425 °C (800 °F), the carbides do not precipitate, and the steels are immune to intergranular corrosion. Reheating the alloys to 425 to 815 °C (800 to 1500 °F), as for stress relief, will cause carbide precipitation and sensitivity to intergranular corrosion. The maximum rate of carbide precipitation occurs at approximately 675 °C (1250 °F). Because this is a common temperature for the stress relief of carbon and low-alloy steels, care must be exercised in selecting stainless steels to be used in dissimilar-metal joints that are to be stress relieved.

Welding is the common cause of the sensitization of stainless steels to intergranular corrosion. Although the cooling rates in the weld itself and the base metal immediately adjacent to it are sufficiently high to avoid carbide precipitation, the weld thermal cycle will bring part of the heat-affected zone (HAZ) into the precipitation range. Carbides will precipitate, and a zone somewhat removed from the weld will become susceptible to intergranular corrosion. Welding does not always sensitize austenitic stainless steels. In thin sections, the thermal cycle may be such that no part of the HAZ is at sensitizing temperatures long enough to cause carbide precipitation. Once the precipitation has occurred, it can be removed by reheating the alloy to above 1035 °C (1895 °F) and cooling it rapidly.

Susceptibility to intergranular corrosion in austenitic stainless steels can be avoided by controlling their carbon contents or by adding elements whose carbides are more stable than those of chromium. For most austenitic stainless steels, restricting their carbon contents to 0.03% or less will prevent sensitization during welding and most heat treatment. This method is not effective for eliminating sensitization that would result from long-term service exposure at 425 to 815 °C (800 to 1500 °F).

Titanium and niobium form more stable carbides than chromium and are added to stainless steels to form these stable carbides, which remove carbon from solid solution and prevent precipitation of chromium carbides. The most common of these stabilized grades are types 321 and 347. Type 321 contains a minimum of [5 × (C + N)]% titanium, and type 347 contains a minimum of (8 × C)% niobium. Nitrogen must be considered when titanium is used as a stabilizer, not because the precipitation of chromium nitride is a problem in austenitic steels, but because titanium nitride is very stable. Titanium will combine with any available nitrogen; therefore, this reaction must be considered when determining the total amount of titanium required to combine with the carbon.

The stabilized grades are more resistant to sensitization by long-term exposure at 425 to 815 °C (800 to 1500 °F) than the low-carbon grades, and the stabilized grades are the preferred materials when service involves exposure at these temperatures. For maximum resistance to intergranular corrosion, these grades are given a stabilizing heat treatment at approximately 900 °C (1650 °F). The purpose of the treatment is to remove carbon from solution at temperatures where titanium and niobium carbides are stable, but chromium carbides are not. Such treatments prevent the formation of chromium carbide when the steel is exposed to lower temperatures.

Ferritic Stainless Steels. The mechanism for intergranular corrosion in ferritic stainless steels is largely accepted as being the same as that in austenitic stainless steels. Chromium compounds precipitate at grain boundaries, and this causes chromium depletion in the grains immediately adjacent to the boundaries. This lowering of the chromium content leads to increased corrosion rates in the oxidizing solutions usually used to evaluate intergranular corrosion.

There are several differences between the sensitization of ferritic and austenitic stainless steels to intergranular corrosion. The first is that the solubility of nitrogen in austenite is great enough that chromium nitride precipitation is not a significant cause of intergranular corrosion in austenitic steels. It is, however, a significant cause in ferritic stainless steels. The second is the temperature at which it occurs. Sensitization in austenitic steels is produced by heating between 425 and 815 °C (800 and 1500 °F). In conventional ferritic alloys, sensitization is caused by heating above 925 °C (1700 °F). This difference is the result of the relative solubilities of carbon and nitrogen in ferrite and austenite.

The most straightforward method of preventing intergranular attack in ferritic stainless steels is to restrict their carbon and nitrogen interstitial contents. For example, more recently developed third-generation ferritic alloys such as 26Cr-1Mo and 29Cr-4Mo (Table 2) have low interstitial contents of 20 ppm C and 100 ppm N. Stabilized grades also help prevent sensitization. Both titanium- and niobium-stabilized steels can be used, and each has advantages. In general, weld ductility is somewhat better in the titanium-containing alloys, but the toughness of the niobium steels is better. However, titanium-stabilized alloys are not recommended for service in nitric acid, but the niobium-containing steels can be used in this environment.

Duplex stainless steels with low carbon contents (0.03%) and approximately equal amounts of austenite and ferrite have very good resistance to sensitization.

475 °C Embrittlement

Iron-chromium alloys containing 13 to 90% Cr are susceptible to embrittlement when held within or cooled slowly through the temperature range of 550 to 400 °C (1020 to 750 °F). This phenomenon, called 475 °C (885 °F) embrittlement, increases tensile strength and hardness and decreases tensile ductility, impact strength, electrical resistivity, and corrosion resistance.

475 °C embrittlement occurs with iron-chromium ferritic and duplex ferritic-austenitic stainless steels, but not with austenitic grades. Aging at 475 °C (885 °F) can cause a rapid rate of hardening with aging between about 20 and 120 h because of homogeneous precipitation. The rate of hardening is much slower with continued aging from 120 to 1000 h. During this aging period, precipitation increases. Aging beyond 1000 h produces little increase in hardness because of the stability of the precipitates.

Even for a severely embrittled alloy, 475 °C embrittlement is reversible. Properties can be restored within minutes by reheating the alloy to 675 °C (1250 °F) or above. The degree of embrittlement increases with chromium content; however, embrittlement is negligible below 13% Cr. Carbide-forming alloying additions, such as molybdenum, vanadium, titanium, and niobium, appear to increase embrittlement, particularly with higher chromium levels. Increased levels of carbon and nitrogen also enhance embrittlement and, of course, are detrimental to nonembrittled properties as well. Cold work prior to 475 °C (885 °F) exposure accelerates embrittlement, particularly for higher-chromium alloys.

Sigma-Phase Embrittlement

The formation of σ phase in ferritic, austenitic, and duplex stainless steels during long periods of exposure to temperatures between approximately 560 and 980 °C (1050 and 1800 °F) results in considerable embrittlement after cooling to room temperature. Sigma phase, an iron-chromium compound approximately equivalent to FeCr, has a tetragonal crystal structure and a hardness equivalent to approximately 68 HRC (940 HV). Because of its brittleness, σ often fractures during indentation.

Sigma phase is formed by either (a) slow cooling from temperatures of 1040 to 1150 °C (1900 to 2100 °F) or (b) water quenching from 1040 to 1150 °C followed by heating at 560 to 980 °C, with heating at 850 °C (1560 °F) producing the greatest effect. The embrittlement is most detrimental after the steel has cooled to temperatures below 260 °C (500 °F). At higher temperatures, stainless steels containing σ phase usually can withstand normal design stresses. However, cooling to 260 °C or below results in essentially complete loss of toughness.

The presence of σ phase greatly increases notch sensitivity, particularly in ferritic stainless steels and austenitic alloys that also contain some ferrite. The hardness and tensile strengths are usually not significantly affected by the presence of σ phase, but the impact strength is greatly affected. Sigma phase exerts a strengthening effect at high temperatures; however, the impact strength at high temperatures of an alloy containing σ phase is lower than the impact strength at room temperature of an alloy without σ phase.

In commercial austenitic and ferritic stainless steels, even small amounts of silicon markedly accelerate the formation of σ. In general, all of the elements that stabilize ferrite promote σ formation. Molybdenum has an effect similar to that of silicon; aluminum has a lesser influence. Increasing the chromium content also favors σ formation. Small amounts of nickel and manganese increase the rate of σ formation, but large amounts, which stabilize austenite, retard σ formation. Carbon additions decrease σ formation by forming chromium carbides, thereby reducing the amount of chromium in solid solution. Additions of tungsten, vanadium, titanium, and niobium also promote σ formation.

As might be expected, σ forms more readily in ferritic than in austenitic stainless steels. Coarse grain sizes from high solution-annealing temperatures retard σ formation, and prior cold working enhances it. The influence of cold work on σ formation depends on the amount of cold work and its effect on recrystallization. If the amount of cold work is sufficient to produce recrystallization at the service temperature, σ formation is enhanced. If recrystallization does not occur, the rate of σ formation may not be affected. Small amounts of cold work that do not promote recrystallization may actually retard σ formation.

Duplex alloys are usually high in chromium (25 to 27%) and molybdenum (2 to 4%). As a result, these alloys are prone to the formation of intermetallic phases such as σ and chi (χ) if they are not cooled rapidly through the 900 to 700 °C (1650 to 1290 °F) range. Although these intermetallic compounds do affect the corrosion resistance of the alloys, they have a more drastic effect on mechanical properties. If a duplex alloy has satisfactory mechanical properties, it probably will not experience intergranular corrosion.

Selected References

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Fabrication of Wrought Stainless Steels

Introduction

FABRICATION of wrought stainless steels differs from fabrication of carbon and low-alloy steels primarily because stainless steels (a) are stronger, harder, and more ductile; (b) work harden more readily; and (c) generally must present a corrosion-resistant surface in the finished product. These characteristics dictate use of greater power, more frequent repair or replacement of processing equipment, and application of procedures to minimize or correct surface contamination.

Forming

The method chosen for forming stainless steel should be based on the characteristics of the type to be used and the thickness of the part to be formed. As indicated previously, power requirements are higher for forming stainless steels than for forming carbon steels--particularly austenitic types, which work harden more rapidly than ferritic types. Warm or hot forming can be necessary for thicknesses that can be formed cold in carbon steel.

Because of their high ductility, austenitic types are the most readily formed stainless steels: austenitic stainless steel sheet can be severely drawn. Austenitic types 201 and 301 can be formed with biaxial stretching in excess of 35% because partial transformation to martensite during deformation helps the metal resist necking and deform more uniformly. (For unusually severe forming, composition may have to be adjusted to suit the particular job, and slow forming may be necessary to prevent buildup of heat and loss of the martensite effect.) Ferritic and lower-alloy martensitic types also can be extensively cold formed. However, they are less ductile than austenitic types, and thus forming of these alloys is more limited, and intermediate annealing is more likely to be needed. The higher-carbon martensitic types such as 440A, 440B, and 440C have only limited cold formability. The higher strength of duplex stainless steels relative to their austenitic counterparts necessitates greater loads in cold-forming operations. Because elongation is less, they should be formed to more generous radii than fully austenitic materials. Heavily cold-formed (>15%) sections should be fully annealed and quenched whenever applications for the alloy present the possibility of stress-corrosion cracking in the service environment.

Stainless steels generally gall more readily than other steels and thus require more attention to lubrication during forming. Straight mineral oils rarely provide adequate lubrication where sliding contact occurs in forming, and lubricants with extreme-pressure additives are often used. Surface contamination during forming and handling should be kept to a minimum by thoroughly cleaning equipment and providing proper lubrication.

Cold formed stainless steel parts usually are used in the as-formed condition. However, for applications in which stress-corrosion cracking can occur, austenitic types susceptible to this failure process should be solution annealed after forming to remove residual stresses. Under all but the mildest service conditions, hot formed parts require postforming annealing to restore corrosion resistance and/or ductility.

Forging

All standard types of stainless steel can be forged. However, as alloy content increases within a given group, forging becomes more difficult. Forging difficulties are most common in initial breakdown of high-alloy ingots, and precautions may be needed to avoid surface ruptures.

Working Temperatures. Figure 1 shows typical forging-temperature ranges for most standard stainless steels. A wide range of forging temperatures can be used for most of the common austenitic types because of the natural workability of austenite and the absence of allotropic transformation. The conventional 18-8 types often are forged at temperatures up to 1260 °C (2300 °F). However, the upper temperature limit is lower for the higher-alloy grades due to metallurgical changes at higher temperatures that can cause surface ruptures. Maximum temperature is lowest for types 309, 310, and 330. Adherence to maximum temperature limits is particularly important for ingot breakdown, where severe tearing along grain boundaries in the cast metal can occur if temperature is too high.

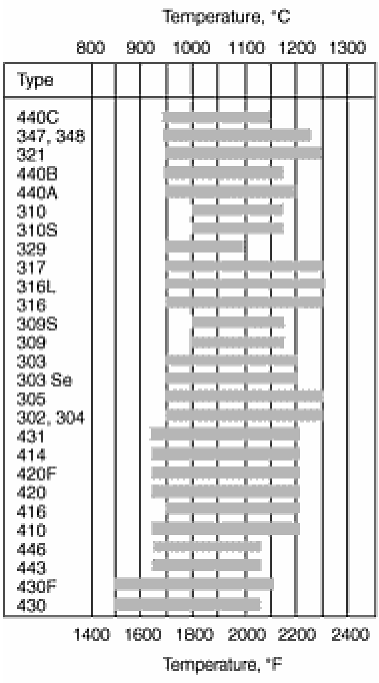

Fig. 1 Typical forging temperature ranges for stainless steels. Alloys toward the top of the figure are more difficult to hot work; those toward the bottom are easier to hot work.

Small amounts of delta ferrite can impair the forgeability of some austenitic types--particularly in upset forging, where some of the tangential tensile forces are perpendicular to ferrite stringers. Types 304, 309, 316, 317, and 321 are especially likely to contain significant amounts of ferrite, and it may be advisable to limit ferrite content of these grades for severe forging applications. Ferrite can be particularly troublesome in initial ingot breakdown; a homogenization treatment at approximately 1150 °C (2100 °F), to transform some of the delta ferrite to austenite before heating to forging temperature, can be helpful.

Austenitic stainless steel forgings should be solution annealed to restore corrosion resistance and maximum ductility. For some applications, annealing can be omitted if working is finished above 870 °C (1600 °F) and the forging is rapidly cooled below 425 °C (800 °F), in order to prevent carbide precipitation. This approach should be used with caution and should incorporate metallurgical checks to determine that detrimental carbide precipitation has actually been avoided. The stabilized types (321, 347, and 348) and extra-low-carbon types (304L and 316L) will not precipitate carbides as readily, and can be used in the as-forged condition with fewer precautions if maximum corrosion resistance and ductility are not essential.

The lower-carbon martensitic stainless steels can be hot worked over a wide temperature range. Finishing temperature is limited only by the allotropic transformation, which begins near 800 °C (1500 °F). The higher-carbon types (420 and 440) have a more limited forging-temperature range because of lower hot ductility. Because all martensitic types are highly hardenable, they require some type of heat treatment (generally annealing) after forging. Except for type 410, which can be used in the annealed condition, martensitic types should be further heat treated, if not for higher hardness then for best corrosion resistance, before being put into service.

Figure 1 shows a broad range of forging temperatures for the ferritic steels. Forging is completed at slightly lower temperatures than for austenitic types because the ferritic types tend to exhibit grain growth and structural weakness. Finishing temperatures are closely restricted only for types 405, 430, and 442. These alloys require special consideration because of grain-boundary weakness due to development of a small amount of austenite. The other ferritic types are commonly finished at temperatures as low as 700 °C (1300 °F). For fully ferritic types such as type 446, at least the final 10% reduction (and preferably more) should be performed below 870 °C (1600 °F) to achieve grain refinement and to develop optimum room-temperature ductility. Annealing after forging is recommended for ferritic types because most of them contain substantial amounts of brittle martensite in the as-forged condition even though this may not be apparent from hardness measurements.

Cold Working

The cold working operations that can be successfully performed on most stainless steels include cold heading, cold drawing, cold extrusion, and cold riveting. Cold working of stainless steel is more difficult than cold working of carbon steel because of differences in strength and work hardening, and power requirements are proportionately greater.

Cold Heading. As a result of the wide differences in work-hardening capabilities among stainless steels, some types are much more adaptable than others to cold heading. The more commonly cold-headed grades include the austenitic types 302, 304, 305, 316, 321, and 384; the ferritic and martensitic types 410, 430, and 431 can also be cold headed. One of the most widely used cold-heading stainless steels is UNS S30430, which is identified by some cold-heading engineers as 302 HQ. It is similar in composition to type 304 except that it contains 3 to 4% Cu, which results in a significant reduction in cold-work hardening characteristics.

The surface finish of the part depends largely on the finish of the wire, which suggests the use of lightly drawn rather than annealed wire. Forming pressure increases with severity of shape, and lubrication of dies is difficult when upsetting is severe. Ferritic and lower-carbon martensitic types behave like carbon or low-alloy steels in cold heading.

Cold headed parts made of austenitic and ferritic stainless steels are most often used in the as-headed condition, although annealing may be needed if service conditions are likely to cause stress-corrosion cracking. Martensitic types are usually heat treated after heading.

Machining

Stainless steels as a class are more difficult to machine than carbon and low-alloy steels because of their higher strength and higher work-hardening rates ("gummy" nature). These characteristics require greater power and lower machining speed, shorten tool life, and sometimes lead to difficulty in obtaining a fine finish on the machined surface. Wide variations exist in these characteristics among the different stainless steels.

Procedures. In machining of stainless steels, special attention must be paid to equipment in order to control the effects of strength and work hardening. Rigid equipment and tooling are necessary to prevent chatter. Chip-curler tools are generally recommended because of the tough, stringy chips produced--particularly in machining austenitic and high-alloy ferritic types. Both high-speed tool steels and cemented carbide cutting tools provide acceptable tool life at production machining speeds.

The following precautions should be instituted to avoid work hardening. Tools should never be permitted to ride or glaze without cutting because the surface can work harden to the extent that cutting tools will become burned before they penetrate the surface. Care should be taken to ensure that hardening from one operation does not interfere with subsequent machining. For example a tripod punch rather than a conventional center punch is preferred for hole location to prevent work hardening at the spot that will be touched first by the drill.

Heavier feeds and lower speeds than those used in machining low-alloy steels are used to minimize work hardening.

Type Variations. Low-alloy martensitic and ferritic stainless steels have machining characteristics much like those of low-alloy steels, whereas the higher-carbon martensitic stainless steels are among the most difficult metals to machine. Austenitic and precipitation-hardening stainless steels vary more widely in machining characteristics within each class than do the ferritic and martensitic grades. Most easily machined are the free-machining alloys, which contain a free-machining additive to form inclusions that significantly improve overall machining characteristics.

The structures of low-alloy martensitic and ferritic stainless steels make these types somewhat brittle, resulting in reasonably good chip breakage. However, hardness levels generally are higher than those of annealed low-alloy steels. The low-alloy martensitic stainless steels often must be machined in the hardened-and-tempered condition (up to 38 HRC), which produces excellent dimensional accuracy and surface finish.

Higher-carbon martensitic stainless steels such as types 420 and 440, and particularly type 440C, are progressively more difficult to machine because of their high annealed hardnesses (up to 240 HB) and the presence of hard, abrasive chromium carbides in their microstructures. The high-chromium ferritic stainless steels such as type 446 are difficult to machine because, like austenitic types, they are "gummy" and produce stringy chips.

Austenitic stainless steels such as types 304 and 316 have tensile strengths of 550 to 620 MPa (80 to 90 ksi) in the annealed condition--the same range of strength as that of annealed 1050 carbon steel. However, austenitic stainless steels exhibit much greater spreads between yield and ultimate strengths and much higher work-hardening rates--particularly the leaner alloys such as types 302 and 304. The machinability of duplex stainless steels is limited by their high annealed strength level, and they are considered less machinable than most standard austenitic grades.

Precipitation-hardening types vary considerably in machining characteristics because of differences in structure. They can be ferritic, martensitic, austenitic or two-phase, so machining characteristics will be characteristic of the structure that exists at the time of machining. Like martensitic types, precipitation-hardening stainless steels sometimes are machined after being heat treated to high strength in order to produce parts with closer tolerances than those obtainable by machining before heat treatment.

As stated previously, free-machining stainless steels are significantly more machinable than their non-free-machining counterparts because they contain small amounts of various free-machining additives. The most common additive is sulfur, which minimizes buildup of metal on cutting edges and promotes chip breakage, thereby permitting higher machining speeds and lower power consumption and promoting longer tool life. The sulfur is present in nonmetallic inclusions, usually complex manganese sulfides. Selenium, which is the second most commonly used free-machining agent in stainless steels, has beneficial effects similar to those of sulfur, but generally gives a better surface finish. Selenium also imparts improved cold formability and somewhat improved corrosion resistance to free-machining stainless steels than does sulfur. Other free-machining additives include tellurium, lead, and bismuth. However, alloys containing these elements are commercially limited due to problems associated with reduced hot workability, erratic machinability associated with the difficulty in obtaining a uniform structure (inclusion morphology) in the steel and/or toxicity.

Because of the high costs of labor and capital, the economic benefits of free-machining stainless steels can be substantial. The free-machining types are slightly more expensive, but this is more than offset by savings in machining costs when extensive machining is required. As a rule, a free-machining type may be cost effective in any application where more than 10% of the material must be machined away.

The characteristics of free-machining types must be carefully considered to ensure that parts will perform satisfactorily in service. Properties that can be degraded by the addition of a free-machining agent include corrosion resistance, transverse ductility and toughness, hot workability, cold formability, and weldability. In some cases, variants of the basic free-machining alloy are available to provide an optimum combination of machinability with another property. However, the tradeoff among the various properties must still be considered when selecting an alloy; that is, the ease of machining must be balanced against the possible reduction in other important properties, such as corrosion resistance.

Table 1 lists some non-free-machining and free-machining alloys within the ferritic, martensitic, and austenitic families. Free-machining alloys are currently unavailable in the duplex or precipitation-hardenable families. Because duplex alloys are noted for excellent corrosion resistance but have somewhat limited hot workability, the addition of a free-machining agent, which would likely degrade both properties, would be undesirable. Similarly, precipitation-hardenable alloys are noted for good toughness at high strength levels, making it undesirable to add a free-machining agent, which would degrade toughness.

Table 1 Available free-machining stainless steel grades

Non-free-machining alloys	Related free-machining alloys	
	Selenium-bearing	**Sulfur-bearing**
Ferritic		
S43000	S43023	S43020
S44400	. . .	S18200[(a)]
		S18235
Martensitic		
S41000	S41623	S41600
		S41610[(b)]
S42000	S42023	S42020
S44004	S44023	S44020
Austenitic		
. . .	. . .	S20300
S30200/S30400	S30323	S30300
		S30310[(b)]
		S30345[(c)]
		S30360[(d)]
S30430	. . .	S30330

		S30431(e)
S31600	. . .	S31620
S34700	S34723	S34720

(a) Does not contain titanium.

(b) Contains high manganese.

(c) Contains aluminum.

(d) Contains lead.

(e) Contains lower copper

Heat Treating

Stainless steels are subjected to various heat treatments depending on the type and on the requirements of the application. These treatments, which include annealing, hardening, and stress relieving, restore desirable properties such as corrosion resistance and ductility to metal altered by prior fabrication operations. Heat treatment is often performed in controlled atmospheres to prevent detrimental surface effects.

Annealing. All types of stainless steels can be annealed. Annealing of austenitic types not only recrystallizes the grains and softens the metal, but also takes chromium carbides into solution in the austenite. Because of the latter effect, the process is sometimes referred to as solution annealing. Temperatures must exceed an intermediate range to avoid sensitization due to carbide precipitation along grain boundaries. Annealing temperatures usually are above 1040 °C (1900 °F), although some types can be annealed at closely controlled temperatures as low as 1010 °C (1850 °F) when fine grain size is important. Time at temperature is kept short to hold surface scaling to a minimum and to control grain growth, which can lead to "orange peel" in forming.

Annealing of austenitic stainless steels is occasionally called quench annealing because the metal must be cooled rapidly, usually by water quenching, to prevent sensitization (except for stabilized and extra-low-carbon types). Precipitation of chromium carbides can severely impair corrosion resistance because chromium is depleted in the matrix immediately adjacent to the carbides and/or because the carbides themselves can induce galvanic corrosion. Therefore, if water quenching is not used, thorough investigation is needed to ensure that sensitization does not occur. The investigation must take actual composition into account because the rate of carbide precipitation varies markedly with composition: a heat of type 304 containing 0.05% carbon may be free of precipitation under cooling conditions that would produce heavy sensitization in the same alloy containing 0.08% carbon. Austenitic stainless steels are softened by recrystallization at the annealing temperature and, unlike most other steels, are not hardened by quenching.

A stabilizing anneal is sometimes performed after conventional annealing for types 321, 347, and 348. Most of the carbon content is combined with titanium in type 321 or with niobium in types 347 and 348 when these types are annealed in the usual manner. A further anneal at 870 to 900 °C (1600 to 1650 °F) for 2 to 4 h followed by rapid cooling precipitates all possible carbon as a titanium or niobium carbide and prevents subsequent precipitation of chromium carbide. It is believed that this special protective treatment is sometimes useful when service conditions are rigorously corrosive--especially when service also involves temperatures from approximately 400 to 870 °C (750 to 1600 °F).

Before annealing or other heat treating operations are performed on austenitic stainless steels, the steel should be cleaned to remove oil, grease, and other carbonaceous residues. Such residues lead to carburization during heat treating, which degrades corrosion resistance.

All martensitic and most ferritic stainless steels can be subcritical annealed (process annealed) by heating into the upper part of the ferrite temperature range or full annealed by heating above the critical temperature into the austenite range, followed by slow cooling. Usual temperatures are 760 to 830 °C (1400 to 1525 °F) for subcritical annealing and 845 to 900 °C (1550 to 1650 °F) for full annealing. When material has been previously heated above the critical temperature, such as in hot working, at least some martensite is present even in ferritic stainless steels such as type 430. Relatively slow cooling at approximately 25 °C/h (50 °F/h) from full annealing temperature, or holding for one hour or more at subcritical annealing temperature, is required to produce the desired soft structure of ferrite and spheroidized carbides. However, parts that have undergone only cold working after full annealing can be subcritically annealed satisfactorily in less than 30 minutes.

The ferritic types that retain predominantly single-phase structures throughout the working temperature range (types 409, 442, 446, and 26Cr-1Mo) require only short recrystallization annealing in the range from 760 to 955 °C (1400 to 1750 °F). The higher-chromium types such as 446 and 26Cr-1Mo require rapid cooling through the range from 540 to 370 °C (1000 to 700 °F) to avoid "885 °F" embrittlement and consequent loss of ductility.

Hardening. Martensitic stainless steels are hardened by austenitizing, quenching, and tempering much like lower-alloy steels. Austenitizing temperatures normally are 980 to 1010 °C (1800 to 1850 °F)--well above the critical temperature. As-quenched hardness increases with austenitizing temperature to approximately 980 °C (1800 °F) and then decreases due to retention of austenite. For some types, the optimum austenitizing temperature may depend on the subsequent tempering temperature.

Preheating before austenitizing is recommended to prevent cracking in high-carbon types and in intricate sections of low-carbon types. Preheating at 790 °C (1450 °F) and then heating to the austenitizing temperature is the most common practice, but very large or extremely intricate parts sometimes are successively preheated at 540 °C (1000 °F) and then at 790 °C (1450 °F) before austenitizing.

Martensitic stainless steels have high hardenability because of their high alloy content. Air cooling from the austenitizing temperature is usually adequate to produce full hardness. Oil quenching is sometimes used, particularly for larger sections. Tempering temperature must be chosen for the optimum combination of hardness, toughness, and corrosion resistance. Parts should be tempered as soon as they have cooled to room temperature--particularly if oil quenching has been used--to avoid delayed cracking. Parts sometimes are refrigerated to -75 °C (-100 °F) before tempering to transform retained austenite--particularly where dimensional stability is important, such as in gage blocks made of type 440C. Tempering at temperatures above 510 °C (950 °F) should be followed by relatively rapid cooling to below 400 °C (750 °F) to avoid "885 °F" embrittlement.

Some precipitation-hardening stainless steels require more complicated heat treatments than standard martensitic types. For instance, a semiaustenitic precipitation-hardening type may require annealing, solution treatment (to condition austenite for transformation on cooling to room temperature), subzero cooling (to complete the transformation of austenite), and aging (to fully harden the alloy). Conversely, martensitic precipitation-hardening types often require nothing more than a simple aging treatment.

Stress Relieving. Stainless steel weldments generally are heated to temperatures below the usual annealing temperature to decrease high residual stresses when full annealing after welding is impossible. Most often, stress relieving is performed on weldments that are too large or intricate for full annealing or on dissimilar-metal weldments consisting of austenitic stainless steel welded to alloy steel. Stress relieving at temperatures below 400 °C (750 °F) is an acceptable practice but results in only modest stress relief.

Stress relieving at 425 to 925 °C (800 to 1700 °F) significantly reduces residual stresses that otherwise might lead to stress-corrosion cracking or dimensional instability in service. One hour at 870 °C (1600 °F) typically relieves approximately 85% of the residual stresses. However, stress relieving in this temperature range also precipitates grain-boundary carbides, resulting in sensitization that severely impairs corrosion resistance in many media. Sensitized austenitic stainless steels are susceptible to intergranular corrosion or stress-assisted intergranular corrosion even in some media that are considered mild. To avoid these effects, it is strongly recommended that a stabilized stainless steel (type 321, 347, or 348) or a low-carbon type (304L or 316L) be used, particularly when lengthy stress relieving is required.

When austenitic stainless steels have been cold worked to develop high strength, low-temperature stress relieving will increase the proportional limit and yield strength (particularly compressive yield strength). A two-hour treatment at 345 to 370 °C (650 to 700 °F) is normally used; temperatures up to 425 °C (800 °F) can be used if resistance to intercrystalline corrosion is not required for the application. Higher temperatures will reduce strength and sensitize the metal and generally are not used for stress relieving cold worked products.

Stress relieving of martensitic or ferritic stainless steel weldments will simultaneously temper both weld and heat-affected zones and for most types will restore corrosion resistance to some degree. However, annealing temperatures are relatively low for these grades, and normal subcritical annealing is the heat treatment usually selected if the weldment is to be heat treated at all.

Joining Processes

Stainless steels are commonly joined by welding, brazing, and soldering. Arc welding is the overwhelming choice for joining stainless steel to stainless steel because it gives a relatively crevice-free joint of high joint efficiency. Procedures and precautions appropriate for the various types are important if optimum corrosion resistance and mechanical properties are to be attained in the completed assembly. Brazing usually is preferred for joining stainless steels to dissimilar metals.

Welding. Stainless steels of all types are weldable by virtually all welding processes. In part, process selection is often dictated by available equipment. Perhaps the simplest and most universal welding process is manual shielded-metal arc welding (SMAW) with coated electrodes. It has been applied to material as thin as 1.2 mm (0.05 in.), and there is no upper limit on thickness. Other very commonly used processes for stainless steels are gas-tungsten arc welding (GTAW), gas-metal arc welding (GMAW), submerged arc welding (SAW), flux-cored arc welding (FCAW), and several forms of resistance welding. The plasma arc welding (PAW), laser-beam welding (LBW), and electron-beam welding (EBW) processes are also used. Stainless steels are rarely joined by gas welding. In oxyacetylene welding of stainless steels, great skill in controlling the welding atmosphere is required to prevent either oxidation or carburization of the weld pool. Regardless of the welding process chosen, major factors that must be considered are (a) corrosion resistance in the weld and heat-affected zones; (b) residual stress, which can lead to distortion, weld cracking, or fissuring; and (c) for martensitic and ferritic types, mechanical properties in the weld, and heat-affected zones.

Austenitic types are the most weldable stainless steels but are also the stainless steels most different in welding behavior from carbon and low-alloy steels. Probably the most important metallurgical factor to consider in planning for austenitic stainless steel weldments is susceptibility to grain-boundary carbide precipitation (sensitization) at moderately elevated temperatures. Material immediately adjacent to the weld is heated to or above the annealing temperature and is free of precipitation. At some distance away--perhaps 3 mm ($\frac{1}{8}$ in.) or more, depending on welding parameters--the base metal is heated to 650 to 870 °C (1200 to 1600 °F), and grain-boundary carbides can precipitate despite the short time at temperature. Carbide precipitation severely impairs corrosion resistance in many media, including the acids most often used for pickling to remove oxide. Nevertheless, because sensitization occurs in such a narrow region of the heat-affected zone, many austenitic stainless steel weldments are used in the as-welded condition without concern.

Brazing. All stainless steels can be brazed, and this process is frequently used for joining stainless steels to other metals. All brazing techniques can be used, but furnace brazing is employed more often than any other technique because it permits brazing to be done in a protective environment (usually hydrogen or vacuum) that prevents oxidation of the stainless steel. Most brazing of austenitic types is performed at temperatures in the sensitization range, and solution annealing after brazing is impossible. Therefore, stabilized or extra-low-carbon types must be used if service conditions might lead to intergranular corrosion of sensitized material. In brazing of martensitic and ferritic types, a brazing filler metal that melts below the critical temperature of 830 °C (1525 °F) is normally used to avoid martensitic hardening. The heat of brazing will temper, and possibly soften, hardened martensitic stainless steels.

Virtually all types of brazing filler metals are used, including silver, nickel, gold, and copper alloys. High-phosphorus, copper-base filler metals should be avoided, however, because they have harmful effects on stainless steels. Certain austenitic types (21Cr-6Ni-9Mn, for instance) should not be brazed with any copper-base filler metal because molten copper attacks the stainless steel during brazing.

Destructive penetration of stainless steel is possible during brazing. A form of stress-corrosion cracking develops in some types if they are brazed while in a highly stressed condition. Penetration during brazing can be prevented by annealing before brazing, by heating parts slowly enough to relieve stresses before the brazing temperature is reached, or by selecting a brazing filler metal that inhibits such penetration. Grain-boundary penetration can also occur if high-temperature brazing alloys that melt above 980 °C (1800 °F) are used. This problem can be minimized by selecting a favorable brazing alloy, using as little brazing alloy as possible and keeping time at temperature short. Welding through or near a brazed joint can also cause penetration of stainless steel and should be avoided.

Use of a silver brazing alloy to which nickel and tin have been added helps minimize crevice corrosion of brazed joints exposed to certain corrosive media such as seawater. Brazing should be done in a protective atmosphere without flux.

Soldering. Although all of the stainless steels can be joined by soldering when the proper techniques are used, these materials are not generally soldered because they are used in applications which involve high strength and/or corrosion/ heat resistance. Nevertheless, soldered stainless steel joints still find applications in architecture, food processing, and plumbing. As with brazing, chromium oxide films must be adequately removed to enhance solderability. Types of soldering processes used to join stainless steels include iron soldering (the soldering iron or bit), torch soldering, furnace and infrared soldering, dip soldering, resistance soldering, induction soldering, and laser soldering.

Principal soldering alloys used to join stainless steels are the tin-lead alloys. Pure tin, tin-antimony, and tin-silver solders are used for food handling and other applications where lead would be hazardous.

Precautions in Welding

The most obvious problem associated with welding of stainless steel is maintenance of uniform resistance to corrosion across the weld zone and the adjacent base-metal zones. This problem is commonly overcome by close control of composition and welding conditions. Sometimes, postweld heat treatment is required to restore corrosion properties altered during welding--particularly in material subject to sensitization.

Sensitization (harmful carbide precipitation) can be avoided, where necessary, by any of three methods:

- *Solution annealing after welding* relieves any residual stresses and improves the structure and corrosion resistance of the weld metal itself. However, solution annealing and the postanneal pickling that it necessitates are costly and inconvenient. Distortion can be a serious problem, particularly if water quenching is used to ensure that general reprecipitation of carbides does not occur during cooling. Postweld annealing is impossible for large weldments such as tanks and pressure vessels.
- *Limitation of carbon content.* Carbides will not precipitate in a weld heat-affected zone if carbon content is low enough. Extra-low-carbon stainless steels such as types 304L and 316L (0.030% max carbon) are commonly used in the United States, and such low carbon contents are necessary for weldments that are to be stress relieved. Even the restriction of carbon content to 0.030% max may not completely protect against sensitization and loss of corrosion resistance in the higher-nickel alloys or in any austenitic stainless steel that has been mildly cold worked. Limitation of carbon to 0.05% max will prevent sensitization in the heat-affected zone under most welding conditions, particularly in light sections. When exposed to strongly oxidizing corrosive media such as hot nitric acid, molybdenum-bearing types 316 and 317 are susceptible to intergranular corrosion in the heat-affected zone due to formation of grain-boundary sigma phase, even when carbides are not precipitated. When weldments of molybdenum-bearing grades are to be used in oxidizing media, it is common practice to subject sensitized samples from each heat to corrosion testing for assessment of susceptibility to intergranular corrosion.
- *Stabilization of carbon.* Sensitization in the heat-affected zone can be prevented by tying up the carbon in titanium carbides (as in type 321) or in niobium carbides (as in types 347 and 348) so that detrimental chromium carbides cannot form. The stabilized grades are also recommended for applications involving long-time exposure to temperatures in the sensitization range, such as in prolonged stress relief or service at high temperatures. However, weldments of stabilized grades heated into the sensitization range and later exposed to certain corrosive media can suffer from severe localized corrosion called "knifeline attack." The stable carbides are partly dissolved in a very narrow zone immediately adjacent to the weld, and during later exposure in the sensitization range, chromium carbides can precipitate. This unusual type of sensitization can be prevented by annealing or stabilization annealing, even locally, after welding.

Weld Cracking. Austenitic stainless steel welds are extremely tough and ductile, and thus cold weld cracking is almost never a problem. However, austenitic stainless steels are susceptible to hot cracking or microfissuring as they cool from the solidus to approximately 980 °C (1800 °F). Microfissuring can be prevented or kept to a minimum by eliminating or reducing tensile stress imposed on the weld during cooling through this range. To some degree, microfissuring can be controlled by controlling concentrations of residual elements such as phosphorus. However, the most common control measure is to ensure the presence of at least 3 to 4% ferrite in the as-deposited weld. Small amounts of this phase seem to prevent the cracking that often occurs in fully austenitic weld metal. Ferrite content is usually estimated on the basis of composition by use of the DeLong diagram, which is a modification of the long-used Schaeffler diagram, or more recently developed weld constitution diagrams developed by the Welding Research Council for more highly alloyed weld metals. DeLong's modification takes into account the potent austenitic stabilization effect of nitrogen. Because ferrite contents calculated in this manner are not completely precise, it is recommended that for critical applications actual ferrite content be determined by magnetic analysis of as-deposited weld metal. For production welds, measurement is especially preferred to calculation in the common instance where a high-ferrite welding electrode is used to weld lower-ferrite base metal. Weld composition then varies with the degree of dilution.

Control of ferrite content is not always an acceptable solution to microfissuring. Ferrite is a magnetic phase, reduces corrosion resistance in some media, and can lead to embrittlement in long-time, elevated-temperature service exposure due to precipitation of sigma phase. Ferrite content in the weld can be reduced significantly (typically by 2 to 4%) by annealing after welding; but where postweld annealing is not possible, fully austenitic welds may be required. Some steels such as type 310 are fully austenitic through the entire specified composition range. Weld cracking can be minimized in fully austenitic stainless steels by welding with low heat input, minimizing restraint, designing for low constraint, and keeping residual elements at low concentrations.

Ferritic types are less ductile than austenitic types and therefore are more susceptible to weld cracking. Certain ferritic stainless steels (type 430, for instance) form significant amounts of martensite on cooling after welding, which increases susceptibility to cold cracking. Preheating at 150 to 230 °C (300 to 450 °F) is recommended to minimize weld cracking in all ferritic types.

In fully ferritic types such as 409, 446, and 26Cr-1Mo, welding causes grain coarsening in the base metal immediately adjacent to the weld. Toughness therefore is reduced, particularly in heavy sections and cannot be restored by postweld heat treatment. Ferritic stainless steels that form austenite at elevated temperatures are not coarsened significantly, but postweld annealing is recommended to transform the resulting martensite and enhance ductility in the heat-affected zone.

Martensitic stainless steels are even more susceptible to weld cracking than ferritic types. Preheating at 200 to 300 °C (400 to 600 °F) generally is required. Postweld annealing is standard practice, particularly for steels with carbon contents greater than 0.20%.

Duplex stainless steels can suffer from weld metal, hydrogen cracking. But the reported incidences have been restricted to cases in which the alloy was heavily cold worked or weld metals experienced high levels of restraint or possessed very high ferrite contents in combination with very high hydrogen levels, as a result of poor control of covered electrodes or the use of hydrogen-containing shielding gas.

Cleaning and Finishing

Proper cleaning and finishing of stainless steel parts are essential for maintenance of the corrosion resistance and appearance for which stainless steels are specified. The degree of care required depends on the nature of the application; the most stringent precautions (such as clean-room assembly and sophisticated postassembly cleaning) are used for critical applications such as nuclear-reactor cores, pharmaceutical and food-handling equipment, and some aerospace applications.

Corrosion of Wrought Stainless Steels

Introduction

THE MECHANISM OF CORROSION PROTECTION for stainless steels differs from that for carbon steels, alloy steels, and most other metals. In these other cases, the formation of a barrier of true oxide separates the metal from the surrounding atmosphere. The degree of protection afforded by such an oxide is a function of the thickness of the oxide layer, its continuity, its coherence and adhesion to the metal, and the diffusivities of oxygen and metal in the oxide. In high-temperature oxidation, stainless steels use a generally similar model for corrosion protection. However, at low temperatures, stainless steels do not form a layer of true oxide. Instead, a passive film is formed. One mechanism that has been suggested is the formation of a film of hydrated oxide, but there is not total agreement on the nature of the oxide complex on the metal surface. However, the oxide film should be continuous, nonporous, insoluble, and self healing if broken in the presence of oxygen.

Passivity exists under certain conditions for particular environments. The range of conditions over which passivity can be maintained depends on the precise environment and on the family and composition of the stainless steel. When conditions are favorable for maintaining passivity, stainless steels exhibit extremely low corrosion rates. If passivity is destroyed under conditions that do not permit restoration of the passive film, then stainless steel will corrode much like a carbon or low-alloy steel.

The presence of oxygen is essential to the corrosion resistance of a stainless steel. The corrosion resistance of stainless steel is at its maximum when the steel is boldly exposed and the surface is maintained free of deposits by a flowing bulk environment. Covering a portion of the surface--for example, by biofouling, painting, or installing a gasket--produces an oxygen-depleted region under the covered region. The oxygen-depleted region is anodic relative to the well-aerated boldly exposed surface, and a higher level of alloy content in the stainless steel is required to prevent corrosion.

With appropriate grade selection, stainless steel will perform for very long times with minimal corrosion, but an inadequate grade can corrode and perforate more rapidly than a plain carbon steel will fail by uniform corrosion. Selection of the appropriate grade of stainless steel is then a balancing of the desire to minimize cost and the risk of corrosion damage by excursions of environmental conditions during operation or downtime.

Confusion exists regarding the meaning of the term passivation. It is not necessary to chemically treat a stainless steel to obtain the passive film; the film forms spontaneously in the presence of oxygen. Most frequently, the function of passivation is to remove free iron, oxides, and other surface contamination. For example, in the steel mill, the stainless steel can be pickled in an acid solution, often a mixture of nitric and hydrofluoric acids (HNO_3-HF), to remove oxides formed in heat treatment. Once the surface is cleaned and the bulk composition of the stainless steel is exposed to air, the passive film forms immediately.

Effects of Composition

Chromium is the one element essential in forming the passive film. Other elements can influence the effectiveness of chromium in forming or maintaining the film, but no other element can, by itself, create the properties of stainless steel. The film is first observed at approximately 10.5% Cr, but it is rather weak at this composition and affords only mild atmospheric protection. Increasing the chromium content to 17 to 20%, as typical of the austenitic stainless steels, or to 26 to 29%, as possible in the newer ferritic stainless steels, greatly increases the stability of the passive film. However, higher chromium can adversely affect mechanical properties, fabricability, weldability, or suitability for applications involving certain thermal exposures. Therefore, it is often more efficient to improve corrosion resistance by altering other elements, with or without some increase in chromium.

Nickel, in sufficient quantities, will stabilize the austenitic structure; this greatly enhances mechanical properties and fabrication characteristics. Nickel is effective in promoting repassivation, especially in reducing environments. Nickel is particularly useful in resisting corrosion in mineral acids. Increasing nickel content to approximately 8 to 10% decreases resistance to stress-corrosion cracking (SCC), but further increases begin to restore SCC resistance. Resistance to SCC in most service environments is achieved at approximately 30% Ni. In the newer ferritic grades, in which the nickel addition is less than that required to destabilize the ferritic phase, there are still substantial effects. In this range, nickel increases yield strength, toughness, and resistance to reducing acids, but it makes the ferritic grades susceptible to SCC in concentrated magnesium chloride ($MgCl_2$) solutions.

Manganese in moderate quantities and in association with nickel additions will perform many of the functions attributed to nickel. However, total replacement of nickel by manganese is not practical. Very high manganese steels have some unusual and useful mechanical properties, such as resistance to galling. Manganese interacts with sulfur in stainless steels to form manganese sulfides. The morphology and composition of these sulfides can have substantial effects on corrosion resistance, especially pitting resistance.

Molybdenum in combination with chromium is very effective in terms of stabilizing the passive film in the presence of chlorides. Molybdenum is especially effective in increasing resistance to the initiation of pitting and crevice corrosion.

Carbon is useful to the extent that it permits hardenability by heat treatment, which is the basis of the martensitic grades, and that it provides strength in the high-temperature applications of stainless steels. In all other applications, carbon is detrimental to corrosion resistance through its reaction with chromium. In the ferritic grades, carbon is also extremely detrimental to toughness.

Nitrogen is beneficial to austenitic stainless steels in that it enhances pitting resistance, retards the formation of the chromium-molybdenum σ phase, and strengthens the steel. Nitrogen is essential in the newer duplex grades for increasing the austenite content, diminishing chromium and molybdenum segregation, and for raising the corrosion resistance of the austenitic phase. Nitrogen is highly detrimental to the mechanical properties of the ferritic grades and must be treated as comparable to carbon when a stabilizing element is added to the steel.

Aluminum. Additions of aluminum enhance high-temperature oxidation resistance.

Niobium is used to combine with carbon, thus reducing the formation of chromium carbides. This reduces the possibility of intergranular corrosion when the stainless is welded or heat treated.

Titanium serves the same purpose as niobium. In some alloys titanium and niobium are used together.

Copper. In some stainless steels copper is added to provide corrosion resistance to sulfuric acid (H_2SO_4).

Silicon. In some alloys silicon is added for high-temperature oxidation resistance. Silicon has also been shown to provide resistance to SCC, as well as resistance to corrosion by oxidizing acids.

Effects of Heat Treatment

Improper heat treatment can produce deleterious changes in the microstructure of stainless steels. The most troublesome problems are carbide precipitation (sensitization) and precipitation of various intermetallic phases, such as sigma (σ), chi (χ), and laves (η).

Sensitization, or carbide precipitation at grain boundaries, can occur when austenitic stainless steels are heated for a period of time in the range of approximately 425 to 870 °C (800 to 1600 °F). Time at temperature will determine the amount of carbide precipitation. When the chromium carbides precipitate in grain boundaries, the area immediately adjacent is depleted of chromium. When the precipitation is relatively continuous, the depletion renders the stainless steel susceptible to intergranular corrosion, which is the dissolution of the low-chromium layer or envelope surrounding each grain. Sensitization also lowers resistance to other forms of corrosion, such as pitting, crevice corrosion, and SCC.

Time-temperature-sensitization curves are available that provide guidance for avoiding sensitization and illustrate the effect of carbon content on this phenomenon (Fig. 1). The curves shown in Fig. 1 indicate that a type 304 stainless steel with 0.062% C would have to cool below 595 °C (1100 °F) within approximately 5 min to avoid sensitization, but a type 304L with 0.030% C could take approximately 20 h to cool below 480 °C (900 °F) without becoming sensitized. These curves are general guidelines and should be verified before they are applied to various types of stainless steels.

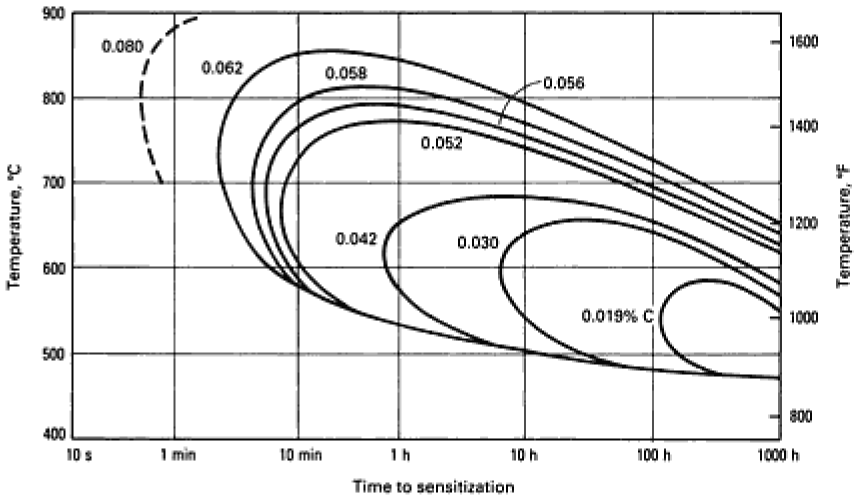

Fig. 1 Time-temperature-sensitization curves for type 304 stainless steel in a mixture of $CuSO_4$ and H_2SO_4 containing free copper. Curves show the times required for carbide precipitation in steels with various carbon contents. Carbides precipitate in the areas to the right of the various carbon content curves.

Another method of avoiding sensitization is to use stabilized steels. Such stainless steels contain titanium and/or niobium. These elements have an affinity for carbon and form carbides readily; this allows the chromium to remain in solution even for extremely long exposures to temperatures in the sensitizing range. Type 304L can avoid sensitization during the relatively brief exposure of welding, but it will be sensitized by long exposures.

Annealing is the only way to correct a sensitized stainless steel. Because different stainless steels require different temperatures, times, and quenching procedures, the user should contact the material supplier for such information. A number of tests can detect sensitization resulting from carbide precipitation in austenitic and ferritic stainless steels. The most widely used tests are described in ASTM standards A 262 and A 763. More detailed information on sensitization of stainless steels can be found in the article "Wrought Stainless Steels: Selection and Application" in this Section.

Precipitation of Intermetallic Phases. Sigma-phase precipitation and precipitation of other intermetallic phases also increase susceptibility to corrosion. Sigma phase is a chromium-molybdenum-rich phase that can render stainless steels susceptible to intergranular corrosion, pitting, and crevice corrosion. It generally occurs in higher-alloyed stainless steels (high-chromium, high-molybdenum stainless steels). Sigma phase can occur at a temperature range between 540 and 900 °C (1000 and 1650 °F). Like sensitization, it can be corrected by solution annealing. Precipitation of intermetallic phases in stainless steels is also covered in the article "Wrought Stainless Steels: Selection and Application" in this Section.

Cleaning Procedures. Any heat treatment of stainless steel should be preceded and followed by cleaning. Steel should be cleaned before heat treating to remove any foreign material that can be incorporated into the surface during the high-temperature exposure. Carbonaceous materials on the surface can result in an increase in the carbon content on the surface, causing carbide precipitation. Salts could cause excessive intergranular oxidation. Therefore, the stainless steel must be clean before it is heat treated.

After heat treatment, unless an inert atmosphere was used during the process, the stainless steel surface will be covered with an oxide film. Such films are not very corrosion resistant and must be removed to allow the stainless steel to form a passive film and provide the corrosion resistance for which it was designed. There are numerous cleaning methods that can be used before and after heat treating. An excellent guide is ASTM A 380.

Effects of Welding

The main problems encountered in welding stainless steels are the same as those seen in heat treatment. The heat of welding (portions of the base metal adjacent to the weld may be heated to 430 to 870 °C, or 800 to 1600 °F) can cause sensitization and formation of intermetallic phases, thus increasing the susceptibility of stainless steel weldments to intergranular corrosion, pitting, crevice corrosion, and SCC. These phenomena often occur in the heat-affected zone of the weld. Sensitization and intermetallic phase precipitation can be corrected by solution annealing after welding. Alternatively, low carbon or stabilized grades can be used.

Another problem in high heat input welds is grain growth, particularly in ferritic stainless steels. Excessive grain growth can increase susceptibility to intergranular attack and reduce toughness. Thus, when welding most stainless steels, it is wise to limit weld heat input as much as possible.

Cleaning Procedures. Before any welding begins, all materials, chill bars, clamps, hold down bars, work tables, electrodes, and wire, as well as the stainless steel, must be cleaned of all foreign matter. Moisture can cause porosity in the weld that would reduce corrosion resistance. Organic materials, such as grease, paint, and oils, can result in carbide precipitation. Copper contamination can cause cracking. Other shop dirt can cause weld porosity and poor welds in general.

Weld design and procedure are very important in producing a sound corrosion-resistant weld. Good fit and minimal out-of-position welding will minimize crevices and slag entrapment. The design should not place welds in critical flow areas. When attaching such devices as low-alloy steel supports and ladders on the outside of a stainless steel tank, a stainless steel intermediate pad should be used. In general, stainless steels with higher alloy content than type 316 should be welded with weld metal richer in chromium, nickel, and molybdenum than the base metal. Every attempt should be made to minimize weld spatter.

After welding, all weld spatter, slag, and oxides should be removed by brushing, blasting, grinding, or chipping. All finishing equipment must be free of iron contamination. It is advisable to follow the mechanical cleaning and finishing with a chemical cleaning. Such a cleaning will remove any foreign particles that may have been embedded in the surface during mechanical cleaning without attacking the weldment. Procedures for such cleaning or descaling are given in ASTM A 380.

Effects of Surface Condition

To ensure satisfactory service life, the surface condition of stainless steels must be given careful attention. Smooth surfaces, as well as freedom from surface imperfections, blemishes, and traces of scale and other foreign material, reduce the probability of corrosion. In general, a smooth, highly polished, reflective surface has greater resistance to corrosion. Rough surfaces are more likely to catch dust, salts, and moisture, which tend to initiate localized corrosive attack.

Oil and grease can be removed by using hydrocarbon solvents or alkaline cleaners, but these cleaners must be removed before heat treatment. Hydrochloric acid (HCl) formed from residual amounts of trichloroethylene, which is used for degreasing, has caused severe attack of stainless steels. Surface contamination can be caused by machining, shearing, and drawing operations. Small particles of metal from tools become embedded in the steel surface and, unless removed, can cause localized galvanic corrosion. These particles are best removed by the passivation treatments described in the section "Passivation Techniques."

Shotblasting or sandblasting should be avoided unless iron-free silica is used; metal shot, in particular, will contaminate the stainless steel surface. If shotblasting or shotpeening with metal grit is unavoidable, the parts must be cleaned after blasting or peening by immersing them in an HNO_3 solution.

Passivation Techniques. During handling and processing operations, such as machining, forming, tumbling, and lapping, particles of iron, tool steel, or shop dirt can be embedded in or smeared on the surfaces of stainless steel components. These contaminants can reduce the effectiveness of the natural oxide (passive) film that forms on stainless steels exposed to oxygen at low temperatures (see the introductory paragraphs to this article). If allowed to remain, these particles can corrode and produce rustlike spots on the stainless steel. To prevent this condition, semifinished or finished parts are given a passivation treatment. This treatment consists of cleaning and then immersing stainless steel parts in a solution of HNO_3 or of HNO_3, plus oxidizing salts. The treatment dissolves the embedded or smeared iron, restores the original corrosion-resistant surface, and maximizes the inherent corrosion resistance of the stainless steel. As shown in Table 1, the composition of the acid bath depends on the grade of stainless steel. The 300 series stainless steels can be passivated in 20 vol% HNO_3. A sodium dichromate ($Na_2Cr_2O_7 \cdot 2H_2O$) addition or an increased concentration of HNO_3 is used for less corrosion-resistant stainless steels to reduce the potential for flash attack.

Table 1 Passivating solutions for stainless steels (non-free-machining grades)

Grade	Passivation treatment
Austenitic 300 series grades or grades with ≥17% Cr (except 440 series)	20 vol% HNO_3 at 50-60 °C (120-140 °F) for 30 min
Straight chromium grades (12-14% Cr), high-carbon/high-chromium grades (440 series), or precipitation-hardening grades	20 vol% HNO_3 plus 22 g/L (3 oz/gal) $Na_2Cr_2O_7 \cdot 2H_2O$ at 50-60 °C (120-140 °F) for 30 min or 50 vol% HNO_3 at 50-60 °C (120-140 °F) for 30 min

Free-machining grades require specialized alkaline-acid-alkaline passivation treatments

Forms of Corrosion of Stainless Steels

General (uniform) corrosion of a stainless steel suggests an environment capable of stripping the passive film from the surface and preventing repassivation. Such an occurrence could indicate an error in grade selection. An example is the exposure of a lower-chromium ferritic stainless steel to a moderate concentration of hot sulfuric acid (H_2SO_4).

Galvanic corrosion results when two dissimilar metals are in electrical contact in a corrosive medium. As a highly corrosion-resistant metal, stainless steel can act as a cathode when in contact with a less noble metal, such as steel. The corrosion of steel parts--for example, steel bolts in a stainless steel construction--can be a significant problem. However, the effect can be used in a beneficial way for protecting critical stainless steel components within a larger steel construction. In the case of stainless steel connected to a more noble metal, consideration must be given to the active-passive condition of the stainless steel. If the stainless steel is passive in the environment, galvanic interaction with a more noble metal is unlikely to produce significant corrosion. If the stainless steel is active or only marginally passive, galvanic interaction with a more noble metal will probably produce sustained rapid corrosion of the stainless steel without repassivation. The most important aspect of galvanic interaction for stainless steels is the necessity of selecting fasteners and weldments of adequate corrosion resistance relative to the bulk material, which is likely to have a much larger exposed area.

Pitting is a localized attack that can produce penetration of a stainless steel with almost negligible weight loss to the total structure. Pitting is associated with a local discontinuity of the passive film. It can be a mechanical imperfection, such as an inclusion or surface damage, or it can be a local chemical breakdown of the film. Chloride is the most common agent for initiation of pitting. Once a pit is formed, it in effect becomes a crevice; the local chemical environment is substantially more aggressive than the bulk environment. This explains why very high flow rates over a stainless steel surface tend to reduce pitting corrosion; the high flow rate prevents the concentration of corrosive species in the pit. The stability of the passive film with respect to resistance to pitting initiation is controlled primarily by chromium and molybdenum. Minor alloying elements can also have an important effect by influencing the amount and type of inclusions (for example, sulfides) in the steel that can act as pitting sites.

Pitting initiation can also be influenced by surface condition, including the presence of deposits, and by temperature. For a particular environment, a grade of stainless steel can be characterized by a single temperature, or a very narrow range of temperatures, above which pitting will initiate and below which pitting will not initiate. It is therefore possible to select a grade that will not be subject to pitting attack if the chemical environment and temperature do not exceed the critical levels. If the range of operating conditions can be accurately characterized, a meaningful laboratory evaluation is possible. Formation of deposits in service can reduce the pitting temperature. Figure 2 compares the relative resistance to pitting of a range of commercial stainless steels.

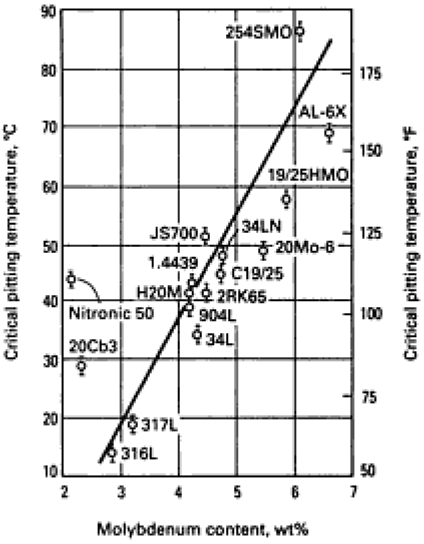

Fig. 2 Effect of molybdenum content on the ferric chloride ($FeCl_3$) critical pitting temperature of commercial stainless steels. The more resistant steels have higher critical pitting temperatures.

Although chloride is known to be the primary agent of pitting attack, it is not possible to establish a single critical chloride limit for each grade. The corrosivity of a particular concentration of chloride solution can be profoundly affected by the presence or absence of various other chemical species that may accelerate or inhibit corrosion. Chloride concentration can increase where evaporation or deposits occur. Because of the nature of pitting attack--rapid penetration with little total weight loss--it is rare that any significant amount of pitting will be acceptable in practical applications.

Crevice corrosion can be considered a severe form of pitting. Any crevice, whether the result of a metal-to-metal joint, a gasket, fouling, or deposits, tends to restrict oxygen access, resulting in attack. In practice, it is extremely difficult to prevent all crevices, but every effort should be made to do so. Higher-chromium, and especially higher-molybdenum, grades are more resistant to crevice attack. Just as there is a critical pitting temperature for a particular environment, there is also a critical crevice temperature (CCT). This temperature is specific to the geometry and nature of the crevice and to the precise corrosion environment for each grade. The CCT can be useful in selecting an adequately resistant grade for particular applications. Table 2 compares the CCT for duplex and austenitic steel grades. The more resistant grades have higher CCTs.

Table 2 Comparison of critical crevice temperature (CCT) for duplex and austenitic stainless steels

UNS No.	Alloy name	CCT in 10% $FeCl_3 \cdot 6H_2O$, pH = 1, 24 h exposure	
		°C	**°F**
Duplex grades			
S32900	Type 329	5	41
S31200	44LN	5	41
S31260	DP-3	10	50

S32950	7-Mo PLUS	15	60
S31803	2205	17.5	63.5
S32250	Ferralium 255	22.5	72.5
Austenitic grades			
S30400	Type 304	<-2.5	<27.5
S31600	Type 316	-2.5	27.5
S31703	Type 317L	0	32
N08020	20Cb-3	0	32
N08366	AL-6N	17.5	63.5
N08367	AL-6XN	32.5	90.5

Intergranular corrosion is a preferential attack at the grain boundaries of a stainless steel. It is generally the result of sensitization. This condition occurs when a thermal cycle leads to grain-boundary precipitation of a carbide, nitride, or intermetallic phase without providing sufficient time for chromium diffusion to fill the locally depleted region. A grain-boundary precipitate is not the point of attack; instead, the low-chromium region adjacent to the precipitate is susceptible.

Sensitization is not necessarily detrimental unless the grade is to be used in an environment capable of attacking the region. For example, elevated-temperature applications for stainless steel can operate with sensitized steel, but concern for intergranular attack must be given to possible corrosion during downtime when condensation might provide a corrosive medium. Because chromium provides corrosion resistance, sensitization also increases the susceptibility of chromium-depleted regions to other forms of corrosion, such as pitting, crevice corrosion, and SCC. The thermal exposures required to sensitize a steel can be relatively brief, as in welding, or can be very long, as in high-temperature service.

Stress-corrosion cracking is a corrosion mechanism in which the combination of a susceptible alloy, sustained tensile stress, and a particular environment leads to cracking of the metal. Stainless steels are particularly susceptible to SCC in chloride environments; temperature and the presence of oxygen tend to aggravate chloride SCC of stainless steels. Most ferritic and duplex stainless steels are either immune or highly resistant to SCC. All austenitic grades, especially AISI types 304 and 316, are susceptible to some degree. The highly alloyed austenitic grades are resistant to sodium chloride (NaCl) solutions but crack readily in $MgCl_2$ solutions. Although some localized pitting or crevice corrosion probably precedes SCC, the amount of pitting or crevice attack can be so small as to be undetectable. Stress corrosion is difficult to detect while in progress, even when pervasive, and can lead to rapid catastrophic failures of pressurized equipment.

It is difficult to alleviate the environmental conditions that lead to SCC. The level of chlorides required to produce stress corrosion is very low. In operation, there can be evaporative concentration or a concentration in the surface film on a heat-rejecting surface. Temperature is often a process parameter, as in the case of a heat exchanger. Tensile stress is one parameter that might be controlled. However, the residual stresses associated with fabrication, welding, or thermal cycling, rather than design stresses, are often responsible for SCC, and even stress-relieving heat treatments do not completely eliminate these residual stresses.

Erosion Corrosion. Corrosion of a metal or alloy can be accelerated when there is an abrasive removal of the protective oxide layer. This form of attack is especially significant when the thickness of the oxide layer is an important factor in determining corrosion resistance. In the case of a stainless steel, erosion of the passive film can lead to some acceleration of attack.

Oxidation. Because of their high chromium contents, stainless steels tend to be very resistant to oxidation. Important factors to be considered in the selection of stainless steels for high-temperature service are the stability of the composition and microstructure of the grade upon thermal exposure and the adherence of the oxide scale upon thermal cycling. Because many of the stainless steels used for high temperatures are austenitic grades with relatively high nickel contents, it is also necessary to be alert to the possibility of sulfidation attack.

Corrosion in Specific Environments

Selection of a suitable stainless steel for a specific environment requires consideration of several criteria. The first is corrosion resistance. Alloys are available that provide resistance to mild atmospheres (for example, type 430) or to many food-processing environments (for example, type 304 stainless). Chemicals and more severe corrodents require type 316 or a more highly alloyed material, such as 20Cb-3. Factors that affect the corrosivity of an environment include the concentration of chemical species, pH, aeration, flow rate (velocity), impurities (such as chlorides), and temperature, including effects from heat transfer.

The second criterion is mechanical properties, or strength. High-strength materials often sacrifice resistance to some form of corrosion, particularly SCC.

Third, fabrication must be considered, including such factors as the ability of the steel to be machined, welded, or formed. Resistance of the fabricated article to the environment must be considered--for example, the ability of the material to resist attack in crevices that cannot be avoided in the design.

Fourth, total cost must be estimated, including initial alloy price, installed cost, and the effective life expectancy of the finished product. Finally, consideration must be given to product availability.

Atmospheric Corrosion

The atmospheric contaminants most often responsible for the rusting of structural stainless steels are chlorides and metallic iron dust. Chloride contamination can originate from the calcium chloride ($CaCl_2$) used to make concrete or from exposure in marine or industrial locations. Iron contamination can occur during fabrication or erection of the structure. Contamination should be minimized, if possible.

The corrosivity of different atmospheric exposures can vary greatly and can dictate application of different grades of stainless steel. Rural atmospheres, uncontaminated by industrial fumes or coastal salt, are extremely mild in terms of corrosivity for stainless steel, even in areas of high humidity. Industrial or marine environments can be considerably more severe.

Most grades of stainless steel are suitable for use in industrial atmospheres, although lower-chromium grades can be unsuitable for more severely contaminated atmospheres. Application often depends on the appearance required. Lower-chromium grades can fulfill service requirements but will tarnish severely. If appearance is important, type 430 is the lowest-alloy grade that can be used, and a higher-alloy grade usually is required.

In atmospheres free from chloride contamination, stainless steels have excellent corrosion resistance. Types 430, 302, 304, and 316 normally do not show even superficial rust. Some rusting can occur in marine atmospheres or in industrial exposures where surfaces become contaminated with chloride salts. Rusting is most likely to be severe on sheltered surfaces that are not well washed by rain.

Although marine environments can be severe, stainless steels often provide good resistance. Table 3 compares several AISI 300 series stainless steels after a 15 year exposure to a marine atmosphere 250 m (800 ft) from the ocean at Kure Beach, NC. Materials containing molybdenum exhibited only extremely slight rust stain, and all grades were easily cleaned to reveal a bright surface. Type 304 stainless steel can provide satisfactory resistance in many marine applications, but more highly alloyed grades are often selected when the stainless is sheltered from washing by the weather and is not cleaned regularly.

Table 3 Corrosion of AISI 300 series stainless steels in a marine atmosphere

AISI type	Average depth of pits		Appearance
	mm	**mils**	
301	0.04	1.6	Light rust and rust stain on 20% of surface
302	0.03	1.2	Spotted with rust stain on 10% of surface
304	0.028	1.1	Spotted with slight rust stain on 15% of surface
321	0.067	2.6	Spotted with slight rust stain on 15% of surface
347	0.086	3.4	Spotted with moderate rust stain on 20% of surface
316	0.025	1.0	Extremely slight rust stain on 15% of surface
317	0.028	1.1	Extremely slight rust stain on 20% of surface
308	0.04	1.6	Spotted by rust stain on 25% of surface
309	0.028	1.1	Spotted by slight rust stain on 25% of surface
310	0.01	0.4	Spotted by slight rust stain on 20% of surface

Based on 15 year exposures 250 m (800 ft) from the ocean at Kure Beach, NC. The average corrosion rate for all specimens tested

Type 302 and 304 stainless steels have had many successful architectural applications. Type 430 stainless steel has been used in many locations, but there have been problems. For example, type 430 stainless steel rusted in sheltered areas after exposure for only a few months in an industrial environment. The type 430 stainless steel was replaced by type 302, which provided satisfactory service. In more aggressive environments, such as marine or severely contaminated atmospheres, type 316 stainless steel is especially useful.

Stress-corrosion cracking is generally not a concern when austenitic or ferritic stainless steels are used in atmospheric exposures. Several austenitic stainless steels were exposed to a marine atmosphere at Kure Beach, NC. Annealed and quarter-hard wrought AISI types 201, 301, 302, 304, and 316 stainless steels were not susceptible to SCC. In the as-welded condition, only type 301 stainless steel experienced failure. Following sensitization at 650 °C (1200 °F) for 1.5 h and furnace cooling, failures were obtained only for materials with carbon contents of 0.043% or more. Stress-corrosion cracking must be considered when quench-hardened martensitic stainless steels or precipitation-hardening grades are used in marine environments or in industrial locations where chlorides are present.

Resistance to SCC is of particular interest in the selection of high-strength stainless steels for fastener applications. Cracking of high-strength fasteners is possible and often results from hydrogen generation due to corrosion or contact with a less noble materials, such as aluminum. Resistance to SCC can be improved by optimizing the heat treatment.

Fasteners for atmospheric exposure have been fabricated from a wide variety of alloys. Type 430 and unhardened type 410 stainless steels have been used when moderate corrosion resistance is required in a lower-strength material. Better-than-average corrosion resistance has been obtained by using type 305 and Custom Flo 302HQ (S30430 containing ~ 3.5% Cu) stainless steels when lower strength is acceptable.

Corrosion in Waters

Waters can vary from extremely pure to chemically treated water to highly concentrated chloride solutions, such as brackish water or seawater, further concentrated by recycling. This chloride content poses the danger of pitting or crevice attack of stainless steels. When the application involves moderately increased temperatures, even as low as 45 °C (110 °F), and particularly when there is heat transfer into the chloride-containing medium, there is the possibility of SCC. It is useful to consider water with two general levels of chloride content: freshwater, which can have chloride levels up to approximately 600 ppm, and seawater, which encompasses brackish and severely contaminated waters. The corrosivity of a particular level of chloride can be strongly affected by the other chemical constituents present, making the water either more or less corrosive.

In freshwater, type 304 stainless steel has provided excellent service for such items as valve parts, weirs, fasteners, and pump shafts in water and wastewater treatment plants. Custom 450 stainless steel has been used as shafts for large butterfly valves in potable water. The higher strength of a precipitation-hardenable stainless steel permits reduced shaft diameter and increased flow. Type 201 stainless steel has seen service in revetment mats to reduce shoreline erosion in freshwater. Type 316 stainless steel has been used as wire for microstrainers in tertiary sewage treatment and is suggested for waters containing minor amounts of chloride.

Seawater is a very corrosive environment for many materials. Stainless steels are more likely to be attacked in low-velocity seawater or at crevices resulting from equipment design or attachment of barnacles. Type 304 and 316 stainless steels suffer deep pitting if the seawater flow rate decreases below approximately 1.5 m/s (5 ft/s) because of the crevices produced by fouling organisms.

The choice of stainless steel for seawater service can depend on whether or not stagnant conditions can be minimized or eliminated. For example, boat shafting of 17Cr-4Ni stainless steel has been used for trawlers where stagnant exposure and the associated pitting would not be expected to be a problem. When seagoing vessels are expected to lie idle for extended periods of time, more resistant boat shaft materials, such as 22Cr-13Ni-5Mn stainless steel, are considered. Boat shafts with intermediate corrosion resistance are provided by 18Cr-2Ni-12Mn and high-nitrogen type 304 (type 304HN) stainless steels.

The most severe exposure conditions are often used in seawater test programs. In one example of such data, flat-rolled specimens of eleven commercially available alloys with several mill finishes were exposed to seawater (Table 4). Triplicate samples were prepared with plastic multiple-crevice washers, each containing 20 plateaus or crevices. These washers were affixed to both sides of each panel by using a torque of either 2.8 or 8.5 N · m (25 or 75 in. · lb). The panels were exposed for up to 90 days in filtered seawater flowing at a velocity of less than 0.1 m/s (<0.33 ft/s).

Table 4 Crevice corrosion indexes of several alloys in tests in filtered seawater

Alloy	UNS designation	Number of sides (S) attacked[(a)]	Maximum pit depth (D)		Crevice corrosion index (S × D)
			mm	**mils**	
AL-29-4C	S44735	0	Nil	Nil	0
MONIT	S44635	3	0.01	0.4	0.03
Ferralium 255	S32550	1	0.09	3.5	0.09

Alloy 904L	N08904	3	0.37	14.6	1.1[(b)]
254SMO	S31254	6	0.19	7.5	1.1
Sea-Cure	S44660	14	0.11	4.3	1.5
AL-6X	N08366	8	0.34	13.4	2.7
JS777	. . .	6	2.3	90.6	14[(b)]
JS700	N08700	14	1.8	70.9	24
AISI type 329	. . .	17	1.6	63	28[(c)]
Nitronic 50	S20910	17	1.2	47.2	20

Mill-finished panels exposed for 30, 60, and 90 days to seawater at 30 °C (85 °F) flowing at <0.1 m/s (<0.33 ft/s). Crevice washers tightened to 2.8 or 8.5 N · m (25 or 75 in. · lb).

(a) Total number of sides was 18.

(b) Also showed tunneling attack perpendicular to the upper edge, or attack at edges.

(c) Perforated by attack from both sides

The results given in Table 4 show the number of sides that experienced crevice attack and the maximum attack depth at any crevice for that alloy. A crevice corrosion index (CCI) was calculated by multiplying the maximum attack depth times the number of sides attacked. This provided a ranking system that accounts for both initiation and growth of attack. Lower values of the CCI imply improved resistance.

Attack in the previously mentioned test does not mean that materials with high CCIs cannot be used in seawater. For example, 22Cr-13Ni-5Mn stainless steel with a CCI of 20 has proved to be a highly resistant boat shaft alloy. Some of the more resistant materials in the previously mentioned tests have been used for utility condenser tubing. These alloys include MONIT, AL-29-4C, 254SMO, Sea-Cure, and AL-6XN.

The possibility of galvanic corrosion must be considered if stainless steel is to be used in contact with other metals in seawater. Preferably, only those materials that exhibit closely related electrode potentials should be coupled to avoid attack of the less noble material. Galvanic differences have been used to advantage in the cathodic protection of stainless steel in seawater. Crevice corrosion and pitting of austenitic type 302 and 316 stainless steels have been prevented by cathodic protection, but type 410 and 430 stainless steels develop hydrogen blisters at current densities below those required for complete protection.

Other factors that should be noted when applying stainless steels in seawater include the effects of high velocity, aeration, and temperature. Stainless steels generally show excellent resistance to high velocities, impingement attack, and cavitation in seawater. Also, stainless steels provide optimum service in aerated seawater because a lack of aeration at a specific site often leads to crevice attack. Very little oxygen is required to maintain the passive film on a clean stainless surface. Increasing the temperature from ambient to approximately 50 °C (120 °F) often reduces attack of stainless steels, possibly because of differences in the amount of dissolved oxygen, changes in the surface film, or changes in the resistance of the boldly exposed sample area. Further temperature increases can result in increased corrosion, such as SCC.

Selection Criteria for Chemical Environments

Selection of stainless steels for service in chemicals requires consideration of all forms of corrosion, along with impurity levels and degree of aeration. When an alloy with sufficient general corrosion resistance has been selected, care must be taken to ensure that the material will not fail by pitting or SCC due to chloride contamination. Aeration can be an important factor in corrosion, particularly in cases of borderline passivity. If dissimilar-metal contact or stray currents occur, the possibility of galvanic attack or hydrogen embrittlement must be considered.

Alloy selection also depends on fabrication and operation details. If a material is to be used in the as-welded or stress-relieved condition, it must resist intergranular attack in service after these thermal treatments. In chloride environments, the possibility of crevice corrosion must be considered when crevices are present because of equipment design or the formation of adherent deposits. Higher flow rates can prevent the formation of deposits, but in extreme cases can also cause accelerated attack due to erosion or cavitation. Increased operating temperatures generally increase corrosion. In heat transfer applications, higher metal wall temperatures result in higher rates than expected from the lower temperature of the bulk solution.

Some generalizations can be made regarding the performance of various categories of stainless steels in certain types of chemical environments. These observations relate to the compositions of the grades. For example, the presence of nickel and copper in some austenitic grades greatly enhances resistance to H_2SO_4 compared to the resistance of the ferritic grades. However, combinations of chemicals that are encountered in practice can be either more or less corrosive than might be expected from the corrosivity of the individual components. Testing in actual or simulated environments is always recommended as the best procedure for selecting a stainless steel grade. Additional information describing service experience is available from alloy suppliers.

Corrosion in Mineral Acids

The resistance of stainless steel to acids depends on the hydrogen ion (H^+) concentration and the oxidizing capacity of the acid, along with such material variables as chromium content, nickel content, carbon content, and heat treatment. For example, annealed stainless steel resists strong HNO_3 in spite of the low pH of the acid, because HNO_3 is highly oxidizing and forms a passive film due to the chromium content of the alloy. Conversely, stainless steels are rapidly attacked by strong HCl because a passive film is not easily attained. Even in strong HNO_3, stainless steels can be rapidly attacked if they contain sufficient carbon and are sensitized. Oxidizing species, such as ferric salts, result in reduced general corrosion in some acids, but can cause accelerated pitting attack if chloride ions (Cl^-) are present.

Nitric Acid. As noted previously, stainless steels have broad applicability in HNO_3 primarily because of their chromium content. Most AISI 300 series stainless steels exhibit good or excellent resistance in the annealed condition in concentrations from 0 to 65% up to the boiling point. Figure 3 illustrates the good resistance of type 304 stainless steel, particularly when compared with the lower-chromium type 410 stainless steel. More severe environments at elevated temperatures require alloys with higher chromium. In HNO_3 cooler-condensers, such stainless alloys as 7-Mo PLUS (UNS S32950) and 2RE10 (UNS S31008), are candidates for service.

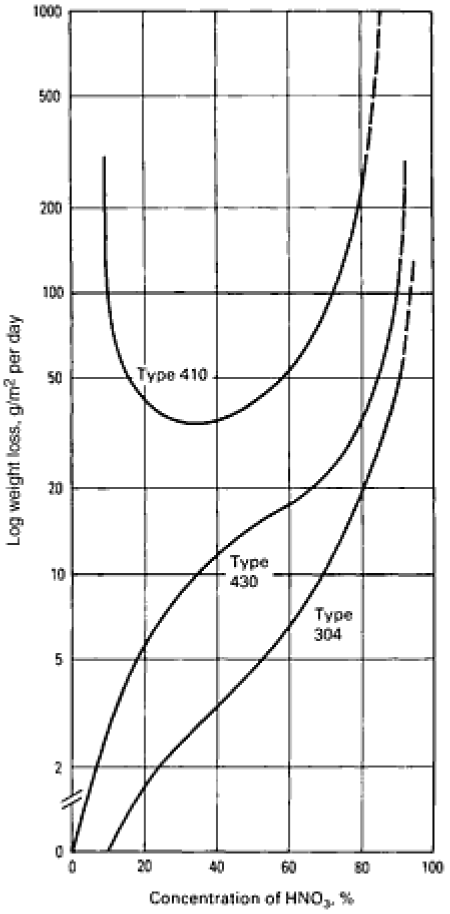

Fig. 3 Corrosion rates of various stainless steels in boiling HNO_3

In sulfuric acid, stainless steels can approach the borderline between activity and passivity. Conventional ferritic grades, such as type 430, have limited use in H_2SO_4, but the newer ferritic grades containing higher chromium and molybdenum (for example, 28% Cr and 4% Mo) with additions of at least 0.25% Ni have shown good resistance in boiling 10% H_2SO_4, but corrode rapidly when acid concentration is increased.

The conventional austenitic grades exhibit good resistance in very dilute or highly concentrated H_2SO_4 at slightly elevated temperatures. Acid of intermediate concentration is more aggressive, and conventional grades have very limited utility. Figure 4 shows resistance of several stainless steels in up to approximately 50% H_2SO_4. Aeration or the addition of oxidizing species can significantly reduce the attack of stainless steels in H_2SO_4. This occurs because the more oxidizing environment is better able to maintain the chromium-rich passive oxide film.

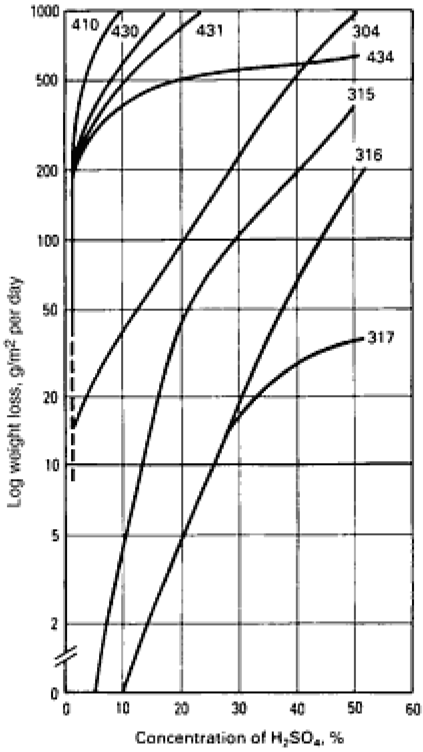

Fig. 4 Corrosion rates of various stainless steels in unaerated H_2SO_4 at 20 °C (70 °F)

Improved resistance to H_2SO_4 has been obtained by using austenitic grades containing high levels of nickel and copper, such as 20Cb-3 stainless steel. In addition to reducing general corrosion, the increased nickel provides resistance to SCC. Because of resistance to these forms of corrosion, 20Cb-3 stainless steel has been used for valve springs in H_2SO_4 service.

Phosphoric Acid. Conventional straight-chromium stainless steels have very limited general corrosion resistance in phosphoric acid (H_3PO_4) and exhibit lower rates only in very dilute or more highly concentrated solutions. Conventional austenitic stainless steels provide useful general corrosion resistance over the full range of concentrations up to approximately 65 °C (150 °F); use at temperatures up to the boiling point is possible for acid concentrations up to approximately 40%.

In commercial applications, however, wet-process H_3PO_4 environments include impurities derived from the phosphate rock, such as chlorides, fluorides, and H_2SO_4. These three impurities accelerate corrosion, particularly pitting or crevice corrosion in the presence of the halogens. Higher-alloyed materials than the conventional austenitic stainless steels are required to resist wet-process H_3PO_4. Candidate materials include alloy 904L, alloy 28, 20Cb-3, 20Mo-4, and 20Mo-6 stainless steels.

Hydrochloric Acid. Stainless steels are generally not used for HCl service, except perhaps for very dilute solutions at room temperature. Stainless materials can be susceptible to accelerated general corrosion, SCC, and pitting in HCl environments.

Sulfurous Acid. Although sulfurous acid (H_2SO_3) is a reducing agent, several stainless steels have provided satisfactory service in H_2SO_3 environments. Conventional austenitic stainless steels have been used in sulfite digestors, and type 316, type 317, and 20Cb-3 have seen service in wet sulfur dioxide (SO_2) and H_2SO_3 environments. Service life is improved by eliminating crevices, including those from settling of suspended solids, or by using molybdenum-containing grades. In some environments, SCC is also a possibility.

Hydrofluoric Acid. Only austenitic stainless steels are recommended for use in hydrofluoric acid (HF), and even these materials have limited resistance to dilute HF. Type 304 has poor resistance to any significant concentration, but type 316 has useful resistance at ambient temperatures and concentrations below 10%. Cold-worked materials--for example type

303 used as a fastener material--have failed rapidly in HF plants. Annealed austenitic stainless steels are also susceptible to SCC in HF environments. Higher alloys such as 20Cb-3 have good resistance to all concentrations of HF at ambient temperatures and to 0 to 10% concentrations at 70 °C (160 °F).

Corrosion in Organic Acids and Compounds

Organic acids and compounds are generally less aggressive than mineral acids because they do not ionize as completely, but they can be corrosive to stainless steels, especially when impurities are present. The presence of oxidizing agents in the absence of chlorides can reduce corrosion rates.

Acetic Acid. Table 5 lists corrosion rates for several stainless steels in acetic acid. Resistance to pure acetic acid has been obtained by using type 316 and 316L stainless steels over all concentrations up to the boiling point. Type 304 stainless steel can be considered in all concentrations below approximately 90% at temperatures up to the boiling point. Impurities present in the manufacture of acetic acid, such as acetaldehyde, formic acid, chlorides, and propionic acid, are expected to increase the attack of stainless steels. Chlorides can cause pitting or SCC.

Table 5 Corrosion of austenitic stainless steels in boiling glacial acetic acid

AISI type	Corrosion rate	
	mm/yr	**mils/yr**
304	0.46	18
321	1.19	47
347	1.04	41
308	1.35	53
310	0.99	39
316	0.015	0.6

Formic acid is one of the more aggressive organic acids, and corrosion rates can be higher in the condensing vapor than in the liquid. Type 304 stainless steel has been used at moderate temperatures. However, type 316 stainless steel or higher alloys, such as 20Cb-3, are often preferred, and high-alloy ferritic stainless steels containing 26% Cr and 1% Mo or 29% Cr and 4% Mo also show some promise.

Other Organic Acids. The corrosivity of propionic and acrylic acids at a given temperature is generally similar to that of acetic acid. Impurities are important and can strongly affect the corrosion rate. In citric and tartaric acids, type 304 stainless steel has been used for moderate temperatures, and type 316 has been suggested for all concentrations up to the boiling point.

Organic Halides. Most dry organic halides do not attack stainless steels, but the presence of water allows halide acids to form and can cause pitting or SCC. Therefore, care should be exercised when using stainless steels in organic halides to ensure that water is excluded.

Other Organic Compounds. Type 304 stainless steel has generally been satisfactory in aldehydes, in cellulose acetate at lower temperatures, and in fatty acids up to approximately 150 °C (300 °F). At higher temperatures, these chemicals require type 316 or 317. Type 316 stainless steel is also used in amines, phthalic anhydride, tar, and urea service.

Stainless steels have been used in the plastic and synthetic fiber industries. Type 420 and 440C stainless steels have been used as plastic mold steels. More resistant materials, such as Custom 450, have been used for extruding polyvinyl chloride (PVC) pipe. Spinnerettes, pack parts, and metering pumps of Custom 450 and Custom 455 stainless steels have been used in the synthetic fiber industry to produce nylon, rayon, and polyesters.

Corrosion in Foods and Beverages

Stainless steels have been relied on in the food and beverage industry because of the lack of corrosion products that could contaminate the process environment and because of the superior cleanability of the stainless steels. The corrosion environment often involves moderately to highly concentrated chlorides on the process side, often mixed with significant concentrations of organic acids. The water side can range from steam heating to brine cooling. Purity and sanitation standards require excellent resistance to pitting and crevice corrosion.

Foods such as vegetables represent milder environments and can generally be handled by using type 304 stainless steel. Sauces and pickle liquors, however, are more aggressive and can pit even type 316 stainless steel. For improved pitting resistance, such alloys as 22Cr-13Ni-5Mn, 904L, 20Mo-4, 254SMO, Al-6XN, and MONIT stainless steels should be considered.

At elevated temperatures, materials must be selected for resistance to pitting and SCC in the presence of chlorides. Stress corrosion must be avoided in heat transfer applications, such as steam jacketing for cooking or processing vessels or in heat exchangers. Cracking can occur from the process or water side or can initiate outside the unit under chloride-containing insulation. Brewery applications of austenitic stainless steels have been generally successful except for a number of cases of SCC of high-temperature water lines. The use of ferritic or duplex stainless steels is an appropriate remedy for the SCC.

Stainless steel equipment should be cleaned frequently to prolong service life. The equipment should be flushed with fresh water, scrubbed with a nylon brush and detergent, then rinsed. On the other hand, consideration should be given to the effect of very aggressive cleaning procedures on the stainless steels, as in the chemical sterilization of commercial dishwashers. In some cases, it may be necessary to select a more highly alloyed stainless steel grade to deal with these brief exposures to highly aggressive environments.

Conventional AISI grades provide satisfactory service in many food and beverage applications. Type 304 stainless steel is widely used in the dairy industry, and type 316 finds application as piping and tubing in breweries. These grades, along with type 444 and Custom 450 stainless steels, have been used for chains to transfer food through processing equipment. Machined parts for beverage-dispensing equipment have been fabricated from type 304, 304L, 316, 316L, and 303Al MODIFIED, 302HQ-FM, and 303BV stainless steels. When the free-machining grades are used, it is important to passivate and rinse properly before service in order to optimize corrosion resistance.

Food-handling equipment should be designed without crevices in which food can become lodged. In more corrosive food products, extra-low-carbon stainless steels should be used when possible. Improved results have been obtained when equipment is finished with a 2B (general-purpose cold-rolled) finish rather than No. 4 (general-purpose polished) finish. Alternatively, an electropolished surface may be considered.

Corrosion in Alkalies

All stainless steels resist general corrosion by all concentrations of sodium hydroxide (NaOH) up to approximately 65 °C (150 °F). Type 304 and 316 stainless steels exhibit low rates of general corrosion in boiling NaOH up to nearly 20% concentration. Stress-corrosion cracking of these grades can occur at approximately 100 °C (212 °F). Good resistance to general corrosion and SCC in 50% NaOH at 135 °C (275 °F) is provided by E-Brite and 7-Mo stainless steels. In ammonia (NH_3) and ammonium hydroxide (NH_4OH), stainless steels have shown good resistance at all concentrations up to the boiling point.

Corrosion in Salts

Stainless steels are highly resistant to most neutral or alkaline nonhalide salts. In some cases, type 316 is preferred for its resistance to pitting, but even the higher-molybdenum type 317 stainless steel is readily attacked by sodium sulfide (Na_2S) solutions.

Halogen salts are more corrosive to stainless steels because of the ability of the halide ions to penetrate the passive film and cause pitting. Pitting is promoted in aerated or mildly acidic oxidizing solutions. Chlorides are generally more aggressive than the other halides in their ability to cause pitting.

Corrosion in Gases

Chlorine and Fluorine Gas. At lower temperatures, most austenitic stainless steels resist chlorine or fluorine gas if the gas is completely dry. The presence of even small amounts of moisture results in accelerated attack, especially pitting and possibly SCC.

Oxidation. At elevated temperatures, stainless steels resist oxidation primarily because of their chromium content. Increased nickel minimizes spalling when temperature cycling occurs. Table 6 lists generally accepted maximum safe service temperatures for wrought stainless steels. Maximum temperatures for intermittent service are lower for the austenitic stainless steels, but are higher for most of the martensitic and ferritic stainless steels listed.

Table 6 Generally accepted maximum service temperatures in air for AISI stainless steels

AISI type	Maximum service temperature			
	Intermittent service		**Continuous service**	
	°C	**°F**	**°C**	**°F**
Austenitic grades				
201	815	1500	845	1550
202	815	1500	845	1550
301	840	1545	900	1650
302	870	1600	925	1700
304	870	1600	925	1700
308	925	1700	980	1795
309	980	1795	1095	2000
310	1035	1895	1150	2100
316	870	1600	925	1700

317	870	1600	925	1700
321	870	1600	925	1700
330	1035	1895	1150	2100
347	870	1600	925	1700
Ferritic grades				
405	815	1500	705	1300
406	815	1500	1035	1895
430	870	1600	815	1500
442	1035	1895	980	1795
446	1175	2145	1095	2000
Martensitic grades				
410	815	1500	705	1300
416	760	1400	675	1250
420	735	1355	620	1150
440	815	1500	760	1400

Contamination of the air with water and CO_2 often increases corrosion at elevated temperatures. Increased attack can also occur because of sulfidation as a result of sulfur dioxide, hydrogen sulfide, or sulfur vapor.

Carburization of stainless steels can occur in carbon monoxide (CO), methane (CH_4), and other hydrocarbons. Carburization can also occur when stainless steels contaminated with oil or grease are annealed without sufficient oxygen to burn off the carbon. This can occur during vacuum or inert gas annealing as well as open air annealing of oily parts with shapes that restrict air access. Chromium, silicon, and nickel are useful in combating carburization.

Nitriding can occur in dissociated ammonia (NH_3) at high temperatures. Resistance to nitriding depends on alloy composition as well as NH_3 concentration, temperature, and pressure. Stainless steels are readily attacked in pure NH_3 at approximately 540 °C (100 °F).

Corrosion in Liquid Metals

The 18-8 stainless steels are highly resistant to liquid sodium or sodium-potassium alloys. Mass transfer is not expected up to 540 °C (1000 °F) and remains at moderately low levels up to 870 °C (1600 °F). Accelerated attack of stainless steels in liquid sodium occurs with oxygen contamination, with a noticeable effect occurring at approximately 0.02% oxygen by weight.

Exposure to molten lead under dynamic conditions often results in mass transfer in common stainless alloy systems. Particularly severe corrosion can occur in strongly oxidizing conditions. Stainless steels are generally attacked by molten aluminum, zinc, antimony, bismuth, cadmium, and tin.

Cast Stainless Steels

Introduction

CAST STAINLESS STEELS are widely used for their corrosion resistance in aqueous media at or near room temperature and for service in hot gases and liquids at elevated temperatures. These high-alloy cast steels generally have more than 10% Cr and primarily consist of stainless steel. Stainless steel castings are usually classified as either corrosion-resistant castings (which are used in aqueous environments below 650 °C, or 1200 °F) or heat-resistant castings (which are suitable for service temperatures above 650 °C, or 1200 °F). However, this line of demarcation in terms of application is not always distinct, particularly for steel castings used in the range from 480 to 650 °C (900 to 1200 °F). The usual distinction between heat-resistant and corrosion-resistant cast steels is based on carbon content, with the heat-resistant grades normally having higher carbon contents.

Comparison of Cast and Wrought Grades

In general, the cast and wrought stainless steels possess equivalent resistance to corrosive media, and they are frequently used in conjunction with each other. Important differences do exist, however, between some cast stainless steels and their wrought counterparts.

Benefits of Ferrite Content. One significant difference between cast and wrought grades is in the microstructure of cast austenitic stainless steels. There is usually a small amount of ferrite present in austenitic stainless steel castings, in contrast to the single-phase austenitic structure of the wrought alloys. The presence of ferrite in the castings is desirable for facilitating weld repair, but ferrite also increases resistance to stress-corrosion cracking (SCC). There have been only a few SCC failures with cast stainless steels in comparison to the approximately equivalent wrought compositions. The principal reasons for this resistance are apparently that silicon added for fluidity gives added benefit from the standpoint of SCC, and that sand castings are usually tumbled or sandblasted to remove molding sand and scale, which probably tends to put the surface in compression.

Ferrite can be detrimental in some applications. One concern may be the reduced toughness from ferrite, although this is not a major concern, given the extremely high toughness of the austenite matrix. A much greater concern is for applications that require exposure to elevated temperatures, usually 315 °C (600 °F) and higher, where the metallurgical changes associated with the ferrite can be severe and detrimental. In applications requiring that these steels be heated in the range from 425 to 650 °C (800 to 1200 °F), carbide precipitation occurs at the edges of the ferrite pools in preference to the austenite grain boundaries. When the steel is heated above 540 °C (1000 °F), the ferrite pools transform to a σ- or χ-phase. If these pools are distributed in such a way that a continuous network is formed, embrittlement or a network of corrosion penetration can result. Also, if the amount of ferrite is too great, the ferrite can form continuous stringers where corrosion can take place, producing a condition similar to grain boundary attack.

Ferrite Control. The major elemental components of cast stainless steels are in competition to promote austenite or ferrite phases in the alloy microstructure. Chromium, silicon, molybdenum, and niobium promote the presence of ferrite in the alloy microstructure; nickel, carbon, nitrogen, and manganese promote the presence of austenite. By balancing the contents of ferrite- and austenite-forming elements within the specified ranges for the elements in a given alloy, it is possible to control the amount of ferrite present in the austenitic matrix. The alloy can usually either be made fully austenitic or be given ferrite contents up to 30% or more in the austenite matrix.

Property Comparisons. Wrought and cast stainless steels may also differ in mechanical properties, magnetic properties, and chemical content. Because of the possible existence of large dendritic grains, intergranular phases, and alloy segregation, typical mechanical properties of cast stainless steels can vary more and generally are inferior to those of any wrought structure.

Grade Designations and Compositions

Cast stainless steels are most often specified on the basis of composition using the designation system of the High Alloy Product Group of the Steel Founders' Society of America. (The High Alloy Product Group has replaced the Alloy Casting Institute, or ACI, which formerly administered these designations.) The first letter of the designation indicates whether the alloy is intended primarily for liquid corrosion service (C) or high-temperature service (H). The second letter denotes the nominal chromium-nickel type of the alloy (Fig. 1). As nickel content increases, the second letter of the designation is changed. The numeral or numerals following the first two letters indicate maximum carbon content (percentage × 100) of the alloy. Finally, if further alloying elements are present, these are indicated by the addition of one or more letters as a suffix. Thus, the designation of CF-8M refers to an alloy for corrosion-resistant service (C) of the 19Cr-9Ni type (Fig. 1), with a maximum carbon content 0.08% and containing molybdenum (M). Similarly, the designation HK-40 refers to an alloy for heat-resistant service (H) of the 26Cr-20Ni type (Fig. 1), with a maximum carbon content of 0.40%.

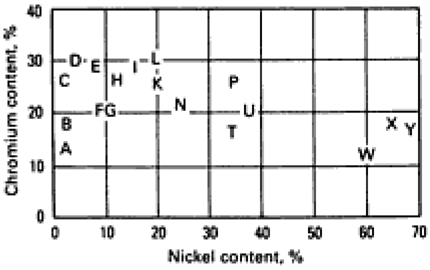

Fig. 1 Chromium and nickel contents in ACI standard grades of heat- and corrosion-resistant steel castings. See text for details.

Some of the high-alloy cast steels exhibit many of the same properties of cast carbon and low-alloy steels. Some of the mechanical properties of these grades (for example, hardness and tensile strength) can be altered by a suitable heat treatment. The cast high-alloy grades that contain more than 20 to 30% Cr plus nickel, however, do not show the phase changes observed in plain carbon and low-alloy steels during heating or cooling between room temperature and the melting point. These materials are therefore nonhardenable, and their properties depend on composition rather than heat treatment. Therefore, special consideration must be given to each grade of high-alloy cast steel with regard to casting design, foundry practice, and subsequent thermal processing (if any).

Corrosion-Resistant Steel Castings

Compositions. The C-type steel castings for liquid corrosion service are often classified on the basis of composition, although it should be recognized that classification by composition often involves microstructural distinction.

Table 1 lists the compositions of the commercial cast corrosion-resistant alloys. Alloys are grouped as chromium steels, chromium-nickel steels (in which chromium is the predominant alloying element), and nickel-chromium steels (in which nickel is the predominant alloying element).

Table 1 Compositions and typical microstructures of corrosion-resistant cast steels

ACI type	UNS No.	Wrought alloy type[(a)]	Microstructure[(b)]	Composition[(c)], %					
				C	**Mn**	**Si**	**Cr**	**Ni**	**Others[(d)]**
Chromium steels									
CA-15	J91150	410	M	0.15	1.00	1.50	11.5-14.0	1.0	0.50Mo[(e)]
CA-15M	J91151	. . .	M	0.15	1.00	0.65	11.5-14.0	1.0	0.15-1.00Mo
CA-40	J91153	420	M	0.40	1.00	1.50	11.5-14.0	1.0	0.5Mo[(e)]
CA-40F	. . .	. . .	M	0.2-0.4	1.00	1.50	11.5-14.0	1.0	. . .
CB-30	J91803	431, 442	F and C	0.30	1.00	1.50	18.0-22.0	2.0	. . .
CC-50	J92615	446	F and C	0.30	1.00	1.50	26.0-30.0	4.0	. . .
Chromium-nickel steels									
CA-6N	. . .	. . .	M	0.06	0.50	1.00	10.5-12.5	6.0-8.0	. . .
CA-6NM	J91540	. . .	M	0.06	1.00	1.00	11.5-14.0	3.5-4.5	0.4-1.0Mo
CA-28MWV	J91422	. . .	M	0.20-0.28	0.50-1.00	1.00	11.0-12.5	0.50-1.00	0.9-1.25Mo; 0.9-1.25W; 0.2-0.3V
CB-7Cu-1	J92180	17-4PH	M, AH	0.07	0.70	1.00	15.5-17.7	3.6-4.6	2.5-3.2Cu; 0.20-0.35Nb; 0.05N max
CB-7Cu-2	J92110	. . .	M, AH	0.07	0.70	1.00	14.0-15.5	4.5-5.5	2.5-3.2Cu; 0.20-0.35 Nb; 0.05N max
CD-4MCu	J93370	. . .	A in F, AH	0.04	1.00	1.00	25.0-26.5	4.75-6.0	1.75-2.25Mo; 2.75-3.25Cu

CE-30	J93423	312	F in A	0.30	1.50	2.00	26.0-30.0	8.0-11.0	. . .
CF-3(f)	J92500	304L	F in A	0.03	1.50	2.00	17.0-21.0	8.0-12.0	. . .
CF-3M(f)	J92800	316L	F in A	0.03	1.50	2.00	17.0-21.0	8.0-12.0	2.0-3.0 Mo
CF-3MN	J92700	. . .	F in A	0.03	1.50	1.50	17.0-21.0	9.0-13.0	2.0-3.0Mo; 0.10-0.20N
CF-8(f)	J92600	304	F in A	0.08	1.50	2.00	18.0-21.0	8.0-11.0	. . .
CF-8C	J92710	347	F in A	0.08	1.50	2.00	18.0-21.0	9.0-12.0	Nb(g)
CF-8M	J92900	316	F in A	0.08	1.50	2.00	18.0-21.0	9.0-12.0	2.0-3.0Mo
CF-10	J92590	. . .	F in A	0.04-0.10	1.50	2.00	18.0-21.0	8.0-11.0	. . .
CF-10M		. . .	F in A	0.04-0.10	1.50	1.50	18.0-21.0	9.0-12.0	2.0-3.0Mo
CF-10MC	J92971	. . .	F in A	0.10	1.50	1.50	15.0-18.0	13.0-16.0	1.75-2.25Mo
CF-10SMnN	. . .	. . .	F in A	0.10	7.00-9.00	3.50-4.50	16.0-18.0	8.0-9.0	0.08-0.18N
CF-12M	. . .	316	F in A or A	0.12	1.50	2.00	18.0-21.0	9.0-12.0	2.0-3.0Mo
CF-16F	J92701	303	A	0.16	1.50	2.00	18.0-21.0	9.0-12.0	1.50Mo max; 0.20-0.35Se
CF-20	J92602	302	A	0.20	1.50	2.00	18.0-21.0	8.0-11.0	. . .
CG-6MMN	J93790	. . .	F in A	0.06	4.00-6.00	1.00	20.5-23.5	11.5-13.5	1.50-3.00Mo; 0.10-0.30Nb; 0.10-30V; 0.20-40N
CG-8M	J93000	317	F in A	0.08	1.50	1.50	18.0-21.0	9.0-13.0	3.0-4.0Mo

CG-12	. . .	. . .	F in A	0.12	1.50	2.00	20.0-23.0	10.0-13.0	. . .
CH-8	J93400	. . .	F in A	0.08	1.50	1.50	22.0-26.0	12.0-15.0	. . .
CH-10	J93401	. . .	F in A	0.04-0.10	1.50	2.00	22.0-26.0	12.0-15.0	. . .
CH-20	J93402	309	A	0.20	1.50	2.00	22.0-26.0	12.0-15.0	. . .
CK-3MCuN	. . .	254SMO	F in A	0.025	1.20	1.00	19.5-20.5	17.5-19.5	6.0-7.0Mo; 0.18-0.24N; 0.50-1.00Cu
CK-20	J94202	310	A	0.20	2.00	2.00	23.0-27.0	19.0-22.0	. . .
Nickel-chromium steel									
CN-3M	. . .	. . .	A	0.03	2.00	1.00	20.0-22.0	23.0-27.0	4.5-5.5Mo
CN-7M	. . .	320	A	0.07	1.50	1.50	19.0-22.0	27.5-30.5	2.0-3.0Mo; 3.0-4.0Cu
CN-7MS	J94650	. . .	A	0.07	1.50	3.50(h)	18.0-20.0	22.0-25.0	2.5-3.0Mo; 1.5-2.0Cu
CT-15C	. . .	. . .	A	0.05-0.15	0.15-1.50	0.50-1.50	19.0-21.0	31.0-34.0	0.5-1.5V

(a) Type numbers of wrought alloys are listed only for nominal identification of corresponding wrought and cast grades. Composition ranges of cast alloys are not the same as for corresponding wrought alloys; cast alloy designations should be used for castings only.

(b) M, martensite; F, ferrite; C, carbides; AH, age hardenable; A, austenite.

(c) Maximum unless a range is given. The balance of all compositions is iron.

(d) Sulfur content is 0.04% in all grades except: CG-6MMN, 0.030% S (max); CF-10SMnN, 0.03% S (max); CT-15C, 0.03% S (max); CK-3MCuN, 0.010% S (max); CN-3M, 0.030% S (max), CA-6N, 0.020% S (max); CA-28MWV, 0.030% S (max); CA-40F, 0.20-0.40% S; CB-7Cu-1 and -2, 0.03% S (max). Phosphorus content is 0.04% (max) in all grades except: CF-16F, 0.17% P (max); CF-10SMnN, 0.060% P (max); CT-15C, 0.030% P (max); CK-3MCuN, 0.045% P (max); CN-3M, 0.030% P (max); CA-6N, 0.020% P (max); CA-28MWV, 0.030% P (max); CB-7Cu-1 and -2, 0.035% P (max).

(e) Molybdenum not intentionally added.

(f) CF-3A, CF-3MA, and CF-8A have the same composition ranges as CF-3, CF-3M, and CF-8, respectively, but have balanced compositions so that ferrite contents are at levels that permit higher mechanical property specifications than those for related grades. They are covered by ASTM A 351.

(g) Nb, 8 × %C min (1.0% max); or Nb + Ta × %C (1.1% max).

(h) For CN-7MS, silicon ranges from 2.50 to 3.50%.

The serviceability of cast corrosion-resistant steels depends greatly on the absence of carbon, and especially precipitated carbides, in the alloy microstructure. Therefore, cast corrosion-resistant alloys are generally low in carbon (usually lower than 0.20% and sometimes lower than 0.03%).

All cast corrosion-resistant steels contain more than 11% Cr, and most contain from 1 to 30% Ni (a few have less than 1% Ni). About two-thirds of the corrosion-resistant steel castings produced in the United States are of grades that contain 18 to 22% Cr and 8 to 12% Ni.

In general, the addition of nickel to iron-chromium alloys improves ductility and impact strength. An increase in nickel content increases resistance to corrosion by neutral chloride solutions and weakly oxidizing acids.

The addition of molybdenum increases resistance to pitting attack by chloride solutions. It also extends the range of passivity in solutions of low oxidizing characteristics.

The addition of copper to duplex (ferrite in austenite) nickel-chromium alloys produces alloys that can be precipitation hardened to higher strength and hardness. The addition of copper to single-phase austenitic alloys greatly improves their resistance to corrosion by sulfuric acid. In all Fe-Cr-Ni stainless alloys, resistance to corrosion by environments that cause intergranular attack can be improved by lowering the carbon content.

Room-Temperature Mechanical Properties. Table 2 gives representative room-temperature tensile properties, hardness, and Charpy impact values for corrosion-resistant cast steels. These properties are representative of the alloys rather than the specification requirements. Minimum specified mechanical properties for these alloys are given in ASTM A 351, A 743, A 744, and A 747. A wide range of mechanical properties are attainable, depending on the selection of alloy composition and heat treatment. Tensile strengths ranging from 475 to 1310 MPa (69 to 190 ksi) and hardnesses from 130 to 400 HB are available among the cast corrosion-resistant alloys. Similarly, wide ranges exist in yield strength, elongation, and impact toughness.

Table 2 Room-temperature mechanical properties of cast corrosion-resistant alloys

Alloy	Heat treatment[a]	Tensile strength		Yield strength (0.2% offset)		Elongation in 50 mm (2 in.), %	Reduction in area, %	Hardness, HB	Charpy impact energy		
		MPa	**ksi**	**MPa**	**ksi**				**J**	**ft · lb**	**Specimens**
CA-6NM	>955 °C (1750 °F), AC, T	827	120	689	100	24	60	269	94.9	70	V-notch
CA-15	980 °C (1800 °F), AC, T	793	115	689	100	22	55	225	27.1	20	Keyhole notch

CA-40	980 °C (1800 °F), AC, T	1034	150	862	125	10	30	310	2.7	2	Keyhole notch
CB-7Cu	1040 °C (1900 °F), OQ, A	1310	190	1172	170	14	54	400	33.9	25	V-notch
CB-30	790 °C (1450 °F), AC	655	95	414	60	15	. . .	195	2.7	2	Keyhole notch
CC-50	1040 °C (1900 °F), AC	669	97	448	65	18	. . .	210	. . .	. . .	. . .
CD-4MCu	1120 °C (2050 °F), FC to 1040 °C (1900 °F), WQ	745	108	558	81	25	. . .	253	74.6	55	V-notch
	1120 °C (2050 °F), FC to 1040 °C (1900 °F), A	896	130	634	92	20	. . .	305	35.3	26	V-notch
CE-30	1095 °C (2000 °F), WQ	669	97	434	63	18	. . .	190	9.5	7	Keyhole notch
CF-3	>1040 °C (1900 °F), WQ	531	77	248	36	60	. . .	140	149.2	110	V-notch
CF-3A	>1040 °C (1900 °F), WQ	600	87	290	42	50	. . .	160	135.6	100	V-notch
CF-8	>1040 °C (1900 °F), WQ	531	77	255	37	55	. . .	140	100.3	74	Keyhole notch
CF-8A	>1040 °C (1900 °F), WQ	586	85	310	45	50	. . .	156	94.9	70	Keyhole notch
CF-20	>1095 °C (2000 °F), WQ	531	77	248	36	50	. . .	163	81.4	60	Keyhole notch
CF-3M	>1040 °C (1900 °F), WQ	552	80	262	38	55	. . .	150	162.7	120	V-notch
CF-3MA	>1040 °C (1900 °F), WQ	621	90	310	45	45	. . .	170	135.6	100	V-notch
CF-8M	>1065 °C (1950 °F), WQ	552	80	290	42	50	. . .	170	94.9	70	Keyhole notch
CF-8C	>1065 °C (1950 °F), WQ	531	77	262	38	39	. . .	149	40.7	30	Keyhole notch
CF-16F	>1095 °C (2000 °F), WQ	531	77	276	40	52	. . .	150	101.7	75	Keyhole notch

CG-8M	>1040 °C (1900 °F), WQ	565	82	303	44	45	. . .	176	108.5	80	V-notch
CH-20	>1095 °C (2000 °F), WQ	607	88	345	50	38	. . .	190	40.7	30	Keyhole notch
CK-20	1150 °C (2100 °F), WQ	524	76	262	38	37	. . .	144	67.8	50	Izod V-notch
CN-7M	1120 °C (2050 °F), WQ	476	69	214	31	48	. . .	130	94.9	70	Keyhole notch

(a) AC, air cool; FC, furnace cool; OQ, oil quench; WQ, water quench; T, temper; A, age

Corrosion Characteristics. As stated earlier, the corrosion characteristics of cast and wrought stainless steels are quite similar (refer to the article "Corrosion of Wrought Stainless Steels" in this Section). Table 3 compares the general corrosion resistance of the C-type cast steels.

Table 3 Summary of applications for various corrosion-resistant cast steels

Alloy	Characteristics
CA-15	Widely used in mildly corrosive environments; hardenable; good erosion resistance
CA-40	Similar to CA-15 at higher strength level
CA-6NM	Improved properties over CA-15, especially improved resistance to cavitation
CA-6N	Outstanding combinations of strength, toughness, and weldability with moderately good corrosion resistance
CB-30	Improved performance in oxidizing environments compared to CA-15; excellent resistance to corrosion by nitric acid, alkaline solutions, and many organic chemicals
CB-7Cu-1	Hardenable with good corrosion resistance
CB-7Cu-2	Superior combination of strength, toughness, and weldability with moderately good corrosion resistance
CC-50	Used in highly oxidizing media (hot HNO_3, acid mine waters)
CD-4MCu	Similar to CF-8 in corrosion resistance, but higher strength, hardness, and stress-corrosion cracking resistance; excellent resistance to environments involving abrasion or erosion corrosion; usefully employed in handling both oxidizing and reducing corrodents
CE-30	Similar to CC-50, but nickel imparts higher strength and toughness levels. A grade available with controlled ferrite

CF-3, CF-8, CF-20, CF-3M, CF-8M, CF-8C, CF-16F	CF types; most widely used corrosion-resistant alloys at ambient and cryogenic temperatures M variations: enhanced resistance to halogen ion and reducing acids C and F variations: used where application does not permit postweld heat treat
CG-8M	Greater resistance to pitting and corrosion in reducing media than CF-8M; not suitable for nitric acids or other strongly oxidizing environments
CH-20	Superior to CF-8 in specialized chemical and paper applications in resistance to hot H_2SO_3, organic acids, and dilute H_2SO_4; the high nickel and chromium contents also make this alloy less susceptible to intergranular corrosion after exposure to carbide-precipitating temperatures
CK-20	Improved corrosion resistance compared to CH-20
CN-7M	Highly resistant to H_2SO_4, H_3PO_4, H_2SO_3, salts, and seawater. Good resistance to hot chloride salt solutions, nitric acid, and many reducing chemicals

Heat-Resistant Steel Castings

As previously mentioned, castings are classified as heat resistant if they are capable of sustained operation while exposed. either continuously or intermittently, to operating temperatures that result in metal temperatures in excess of 650 °C (1200 °F). The major difference between heat-resistant alloys and their corrosion-resistant counterparts is their carbon content. With only a few exceptions, carbon in the cast heat-resistant alloys falls in a range from 0.3 to 0.6%, compared with 0.01 to 0.25% C normally associated with the wrought and cast corrosion-resistant grades. This difference in carbon results in significant changes in properties, for example, the increased carbon content imparts higher creep-rupture strength in the cast heat-resistant steels.

Table 4 lists the compositions of standard cast heat-resistant grades. These materials, which are also recognized in ASTM specifications, fall in a range of 0 to 68% Ni and 8 to 32% Cr with the balance consisting of iron plus up to 2.5% Si and 2.0% Mn.

Table 4 Compositions of standard heat-resistant casting alloys

Wrought alloy type[(a)]	ACI designation	UNS No.	Composition[(b)], %			
			C	**Cr**	**Ni**	**Si (max)**
. . .	HA	. . .	0.20 max	8-10	. . .	1.00
446	HC	J92605	0.50 max	26-30	4 max	2.00
327	HD	J93005	0.50 max	26-30	4-7	2.00
312	HE	J93403	0.20-0.50	26-30	8-11	2.00
302B	HF	J92603	0.20-0.40	19-23	9-2	2.00
309	HH	J93503	0.20-0.50	24-28	11-14	2.00

...	HI	J94003	0.20-0.50	26-30	14-18	2.00
310	HK	J94224	0.20-0.60	24-38	18-22	2.00
...	HK-30	J94203	0.25-0.35	23.0-27.0	19.0-22.0	1.75
...	HK-40	J94204	0.35-0.45	23.0-27.0	19.0-22.0	1.75
...	HL	N08604	0.20-0.60	28-32	18-22	2.00
...	HN	J94213	0.20-0.50	19-23	23-27	2.00
...	HP	N08705	0.35-0.75	24-28	33-37	2.00
...	HP-50WZ(c)	...	0.45-0.55	24-28	33-37	2.50
330	HT	N08605	0.35-0.75	13-17	33-37	2.50
...	HT-30	N08603	0.25-0.35	13.0-17.0	33.0-37.0	2.50
...	HU	N08005	0.35-0.75	17-21	37-41	2.50
...	HW	N08006	0.35-0.75	10-14	58-62	2.50
...	HX	N06050	0.35-0.75	15-19	64-68	2.50

(a) Type numbers of wrought alloys are listed only for nominal identification of corresponding wrought and cast grades. Composition ranges of cast alloys are not the same as for corresponding wrought alloys; cast alloy designations should be used for castings only.

(b) Balance Fe in all compositions. Manganese content: 0.35 to 0.65% for HA, 1% for HC, 1.5% for HD, and 2% for the other alloys. Phosphorus and sulfur contents: 0.04% (max) for all but HP-50WZ. Molybdenum is intentionally added only to HA, which has 0.90 to 1.20% Mo; maximum for other alloys is set at 0.5% Mo. HH also contains 0.2% N (max).

(c) Also contains 4 to 6% W, 0.1 to 1.0% Zr, and 0.035% S (max) and P (max)

Standard heat-resistant alloys can also be simply classified on the basis of structure alone. Grades HA and HC with 8 to 30% Cr and up to 4% Ni are ferritic. Grades HD, HE, HF, and HH may exhibit duplex structures of ferrite and austenite, while the remaining alloys HK to HX are fully austenitic.

A third alternative classification is based on the order of increasing quantity of major elements, which breaks down into the following four groups:

- Iron-chromium
- Iron-chromium-nickel

- Iron-nickel-chromium
- Nickel-iron-chromium

Iron-Chromium Alloys. The three alloys normally considered in this group are HA, HC, and HD, although only the first of these is technically an iron-chromium alloy. The other two grades contain 26 to 30% Cr and up to 7% Ni. These grades are mainly used in environments containing sulfur-bearing gases, where high-temperature strength is not an important consideration.

Iron-Chromium-Nickel Alloys. Alloys in this group contain 18 to 32% Cr and 8 to 22% Ni, with chromium always exceeding nickel, and include the grades HE, HF, HH, HI, HK, and HL. While these alloys are considered to be austenitic, the lower nickel compositions will contain some ferrite. Transformation of the ferrite to brittle σ phase is a concern with this group, even in the higher nickel grades, particularly if their compositional balance leans to ferrite. The high-temperature strength of this group is greater than that of the iron-chromium alloys, and their creep and rupture strengths increase as nickel is raised.

Iron-Nickel-Chromium Alloys. The four standard grades in this group, HN, HP, HT, and HU, contain 15 to 28% Cr and 23 to 41% Ni. Nickel always exceeds the chromium content. These alloys have stable austenitic structures, good high-temeprature strength, and enhanced resistance to thermal cycling and thermal stresses, combined with high resistance to oxidizing and reducing environments.

Nickel-Iron-Chromium Alloys. Two standard grades, HX and HW, fall into this group, which contains 58 to 68% Ni and 10 to 19% Cr. Usually referred to as high-alloy steels, these materials are more correctly described as nickel-base alloys. While possessing moderate high-temperature rupture strength, their creep strength is low. These grades have the highest carburization resistance of the standard alloys.

Nonstandard Grade Compositions. Nonstandard (proprietary) grades of heat-resistant alloys are generally more highly alloyed. Single or multiple additions of the elements aluminum, cobalt (up to 15%), molybdenum (0.5 to 1.5%), niobium (0.5 to 1.5%), the rare earth metals (cerium, lanthanum, and yttrium), titanium (0.1 to 0.3%), tungsten (generally 1 to 5%, but as high as 16%), and zirconium are added to enhance specific properties, such as high-temperature strength, carburization resistance, and resistance to thermal cycling.

General Properties. Table 5 gives typical room-temperature tensile properties of heat-resistant steels castings, creep properties of selected alloys are listed in Table 6, and high-temperature corrosion characteristics are compared in Table 7. Minimum specified mechanical properties for these alloys are given in ASTM A 297, A 351, A 447, and A 608.

Table 5 Typical room-temperature properties of heat-resistant casting alloys

Alloy	Condition	Tensile strength		Yield strength		Elongation, %	Hardness, HB
		MPa	**ksi**	**MPa**	**ksi**		
Standard grades							
HA	N + T[(a)]	738	107	558	81	21	220
HC	As-cast	760	110	515	75	19	223
	Aged[(b)]	790	115	550	80	18	. . .
HD	As-cast	585	85	330	48	16	90

HE	As-cast	655	95	310	45	20	200
	Aged(b)	620	90	380	55	10	270
HF	As-cast	635	92	310	45	38	165
	Aged(b)	690	100	345	50	25	190
HH, type 1	As-cast	585	85	345	50	25	185
	Aged(b)	595	86	380	55	11	200
HH, type 2	As-cast	550	80	275	40	15	180
	Aged(b)	635	92	310	45	8	200
HI	As-cast	550	80	310	45	12	180
	Aged(b)	620	90	450	65	6	200
HK	As-cast	515	75	345	50	17	170
	Aged(c)	585	85	345	50	10	190
HL	As-cast	565	82	360	52	19	192
HN	As-cast	470	68	260	38	13	160
HP	As-cast	490	71	275	40	11	170
HT	As-cast	485	70	275	40	10	180
	Aged(c)	515	75	310	45	5	200
HU	As-cast	485	70	275	40	9	170
	Aged(d)	505	73	295	43	5	190
HW	As-cast	470	68	250	36	4	185
	Aged(e)	580	84	360	52	4	205

HX	As-cast	450	65	250	36	9	176
	Aged[d]	505	73	305	44	9	185

(a) Normalized and tempered at 675 °C (1250 °F).

(b) Aging treatment: 24 h at 760 °C (1400 °F), furnace cool.

(c) Aging treatment: 24 h at 760 °C (1400 °F), air cool.

(d) Aging treatment: 48 h at 980 °C (1800 °F), air cool.

(e) Aging treatment: 48 h at 980 °C (1800 °F), furnace cool

Table 6 Creep properties of selected standard cast heat-resistant alloys

Grade	Temperature		Creep stress to produce 1% creep in 10,000 h		Stress to rupture in 10,000 h		Stress to rupture in 100,000 h	
	°C	**°F**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**
Fe-Cr-Ni								
HF	650	1200	124	18.0	114	16.5	76	11.0
	760	1400	47	6.8	42	6.1	28	4.0
	870	1600	27	3.9	19	2.7	12	1.7
HH	650	1200	124	18.0	97	14.0	62	9.0
	760	1400	43	6.3	33	4.8	19	2.8
	870	1600	27	3.9	15	2.2	8	1.2
	980	1800	14	2.1	6	0.9	3	0.4
HK	760	1400	70	10.2	61	8.8	43	6.2
	870	1600	41	6.0	26	3.8	17	2.5

	980	1800	17	2.5	12	1.7	7	1.0
Fe-Ni-Cr								
HN	870	1600	43	6.3	33	4.8	22	3.2
	980	1800	16	2.4	14	2.1	9	1.3
HT	760	1400	55	8.0	58	8.4	39	5.6
	870	1600	31	4.5	26	3.7	16	2.4
	980	1800	14	2.0	12	1.7	8	1.1
HU	760	1400	59	8.5	. . .	. . .	. . .	. . .
	870	1600	34	5.0	23	3.3	. . .	. . .
	980	1800	15	2.2	12	1.8	. . .	. . .
HX	760	1400	44	6.4	. . .	. . .	. . .	. . .
	870	1600	22	3.2	. . .	. . .	. . .	. . .
	980	1800	11	1.6	. . .	. . .	. . .	. . .

Some stress values are extrapolated.

Table 7 General corrosion characteristics of heat-resistant cast steels

Alloy	Corrosion characteristics
HA	Good oxidation resistance to 650 °C (1200 °F); widely used in oil refining industry
HC	Good sulfur and oxidation resistance up to 1095 °C (2000 °F); minimal mechanical properties; used in applications where strength is not a consideration or for moderate load bearing up to 650 °C (1200 °F)
HD	Excellent oxidation and sulfur resistance plus weldability
HE	Higher temperature and sulfur resistant capabilities than HD
HF	Excellent general corrosion resistance to 815 °C (1500 °F) with moderate mechanical properties

HH	High strength; oxidation resistant to 1090 °C (2000 °F); most widely used
HI	Improved oxidation resistance compared to HH
HK	Because of high-temperature strength, widely used for stressed parts in structural applications up to 1150 °C (2100 °F); offers good resistance to corrosion by hot gases, including sulfur-bearing gases, in both oxidizing and reducing conditions (although HC, HE, and HI are more resistant in oxidizing gases); used in air, ammonia, hydrogen, and molten neutral salts; widely used for tubes and furnace parts
HL	Improved sulfur resistance compared to HK; especially useful where excessive scaling must be avoided
HN	Very high strength at high temperatures; resistant to oxidizing and reducing flue gases
HP	Resistant to both oxidizing and carburizing atmospheres at high temperatures
HP-50WZ	Improved creep rupture strength at1090 °C (2000 °F) and above compared to HP
HT	Widely used in thermal shock applications; corrosion resistant in air, oxidizing and reducing flue gases, carburizing gases, salts, and molten metals; performs satisfactorily up to 1150 °C (2100 °F) in oxidizing atmospheres and up to 1095 °C (2000 °F) in reducing atmospheres, provided that limiting creep stress values are not exceeded
HU	Higher hot strength than HT and often selected for superior corrosion resistance
HW	High hot strength and electrical resistivity; performs satisfactorily to 1120 °C (2050 °F) in strongly oxidizing atmospheres and up to 1040 °C (1900 °F) in oxidizing or reducing products of combustion that do not contain sulfur; resistant to some salts and molten metals
HX	Resistant to hot-gas corrosion under cycling conditions without cracking or warping; corrosion resistant in air, carburizing gases, combustion gases, flue gases, hydrogen, molten cyanide, molten lead, and molten neutral salts at temperatures up to 1150 °C (2100 °F)

Powder Metallurgy Stainless Steels

Introduction

STAINLESS STEEL powder metallurgy (P/M) parts represent an important and growing segment of the P/M industry. Commercial production of P/M stainless steels in North America began in the late 1950s. In the first decade of rapid commercialization of P/M stainless steel, use increased at a compound rate of nearly 20% to reach a consumption of 2000 tons/year in 1973 in North America. Since that time, the industry has continued to grow at a compound rate of approximately 4.6%. According to the Metal Powder Industries Federation (MPIF), the annual production of sintered stainless steel parts in North America is presently (circa 1997 to 1998) approximately 500 tons. The primary market for P/M stainless steels is the automotive industry. Major applications include antilock brake system (ABS) sensor rings, rear-view mirror brackets, and flanges for connecting various exhaust system components. Hardware (e.g., lock components and fasteners), electrical and electronic components (e.g., switches and magnetic clutches), and controlled porosity components for filtration and metering of gases and liquids also consume substantial quantities of P/M stainless steels.

This article will describe the processing and properties of medium-density and high-density P/M stainless steels. Medium-density materials are processed by pressing and sintering prealloyed stainless powders. They achieve densities in the range of 6.4 to 7.2 g/cm^3 (approximately 80 to 90% of theoretical density). High-density materials are produced by hot isostatic pressing, cold isostatic pressing followed by extrusion, or metal injection molding. Densities in these materials approach (95 to 99%) or reach 100% of theoretical density.

Sintered P/M Stainless Steels

Processing

Powder Production. All commercial compacting-grade stainless steel powders are produced by atomization. Most powders that are conventionally pressed and sintered are water atomized. This process produces a powder that is fully alloyed and that has an irregular particle shape and sufficient compressibility and green strength to be suitable for P/M fabrication. Gas (nitrogen) atomization is used to produce spherical powder for high-density applications. These powder morphologies are similar to the tool steel powders shown in the preceding Section "Tool Steels" in this Handbook.

Compaction and Lubrication. Design and processing of stainless steel P/M parts are subject to the same basic considerations as for other P/M materials. However, compared with low-alloy ferrous powders, stainless steel powders require higher compacting pressures and have lower green strength. Figure 1 shows typical compaction characteristics of austenitic and martensitic grades. Compaction pressures ranging from 550 to 830 MPa (40 to 60 tsi) are common in commercial practice.

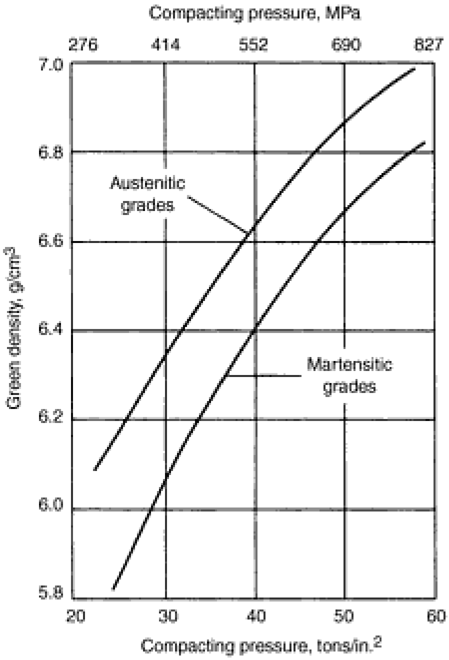

Fig. 1 Typical compaction behavior of stainless steel powders. Lubrication 1% lithium stearate

The green strength of stainless steel compacts, which is about half that of P/M iron, is influenced by compaction pressure and the type of lubricant. (For the manufacture of P/M structural parts, a lubricant is used with the prealloyed powder to facilitate compaction of the powder and the ejection of the part from the die.) Lubricants that provide high green strength, such as stearic acid, generally cause lower compressibility. Therefore, lubricant selection is an important factor in determining successful application and fabrication of stainless steel. Lithium stearate and synthetic waxes are popular lubricants.

Lubricant removal (delubrication), prior to the actual sintering operation, is vitally important for several reasons. Generally, this removal is accomplished during the sintering preheat operation and is referred to as "burn off." Because of highly adverse effects of residual lubricant carbon when sintering stainless steel, resulting in lowered corrosion resistance, burn-off temperatures ranging from 425 to 480 °C (800 to 900 °F) in conjunction with the use of synthetic wax lubricants are commonly employed.

Sintering. Most commercial sintering of stainless steel parts is completed in belt, pusher, walking beam, and vacuum furnaces. Typical sintering atmospheres include dissociated ammonia (75 vol% H and 25 vol% N), H_2-N_2 mixtures, and hydrogen, all with a low dew point (-40 to -55 °C, or -40 to -65 °F), and vacuum. Sintering temperatures range from 1120 to 1345 °C (2050 to 2450 °F)--higher sintering temperatures are used when improved mechanical properties and corrosion resistance are required--and sintering times range from 20 to 60 min. Insufficient sintering, either too short a time or at too low a temperature, will result in sintered parts showing insufficient bonding, original particle boundaries, and sharp, angular pores. Such sintering produces parts with a high concentration of interstitials (carbon and oxygen), low corrosion resistance, and inferior mechanical properties.

Sintering in Dissociated Ammonia (DA). Sintering at 1120 °C (2050 °F) in DA was the most widely used method for sintering stainless steels in the 1960s and 1970s. Dissociated ammonia is not only less expensive than hydrogen, but it also increases strength (with some reduction in ductility) to levels comparable to wrought stainless steels of the same designation. Densities of approximately 85 to 90% of theoretical are achieved. The strengthening is the result of nitrogen absorption during sintering. Nitrogen absorption, however, leads to the formation of chromium nitride (Cr_2N) precipitation with accompanying chromium depletion and deterioration of corrosion resistance (i.e., sensitization, or grain-boundary corrosion). Nitrogen absorption can be decreased by very rapid cooling rates (>200 °C/min, or 360 °F/min) combined with higher dew points, but such sintering practices lead to excessive oxidation. It should also be noted that such cooling rates are not attainable with most commercial atmosphere furnaces.

Sintering in 90% H_2-10% N_2 mixtures is a compromise between sintering in DA and hydrogen atmospheres. Such mixed atmospheres reduce the high cooling rate requirements of DA atmospheres while still supplying solid-solution strengthening and improved corrosion resistance.

Sintering in Hydrogen. With increasing demands for improved corrosion resistance of P/M stainless steels, and as more quantitative information on the effects of sintering in DA atmospheres became available, stainless steel parts producers increasingly shifted toward the use of the more expensive hydrogen atmospheres. The combination of a high sintering temperature (1230 °C, or 2250 °F), low dew point (-50 °C, or -60 °F), and a rapid cooling rate (85 °C/min, or 150 °F/min) produces stainless steel parts containing less than 3000 ppm N_2 and leads to optimum corrosion performance, lower strength, and higher ductility.

Sintering in Vacuum. The principal alternative to DA-based or hydrogen-base atmospheres is vacuum. With a state-of-the-art vacuum furnace, it is much easier to maintain a low dew point and to obtain rapid cooling than is possible with a typical atmosphere furnace. For maximum corrosion resistance of vacuum-sintered stainless steel, surface depletion of chromium due to high vapor pressure and the presence of original surface oxides must be minimized. Sintering under a partial pressure of nitrogen or argon of approximately 1500 μm Hg effectively reduces chromium losses. For minimizing interstitials (carbon, oxygen, and nitrogen), high-temperature vacuum sintering is superior to high-temperature atmosphere sintering. As a result, magnetic properties of vacuum-sintered ferritic stainless steels are superior to those obtained with atmosphere sintering.

Compositions and Properties

Compositions of widely used commercial grades of stainless steels are given in Table 1. Modified versions of these standard MPIF grades include alloys containing 1 to 2% Sn, 2% Cu, or 6% Mo for improved corrosion resistance; alloys containing 3% Si to facilitate liquid-phase sintering to achieve higher densities (7.4 g/cm^3) and improved corrosion resistance; and alloys containing manganese sulfide additions for improved machinability.

Table 1 Compositions of standard (MPIF) P/M stainless steels

Designation	Composition[(a)], wt%									
	Fe	**Cr**	**Ni**	**Mn**	**Si**	**S**	**C**	**P**	**Mo**	**N**
SS-303N1, N2	bal	17.0-19.0	8.0-13.0	0-2.0	0-1.0	0.15-0.30	0-0.15	0-0.20	. . .	0.20-0.60
SS-303L	bal	17.0-19.0	8.0-13.0	0-2.0	0-1.0	0.15-0.30	0-0.03	0-0.20	. . .	0-0.03
SS-304N1, N2	bal	18.0-20.0	8.0-12.0	0-2.0	0-1.0	0-0.03	0-0.08	0-0.045	. . .	0.20-0.60
SS-304L	bal	18.0-20.0	8.0-12.0	0-2.0	0-1.0	0-0.03	0-0.03	0-0.045	. . .	0-0.03
SS-316N1, N2	bal	16.0-18.0	10.0-14.0	0-2.0	0-1.0	0-0.03	0-0.08	0-0.045	2.0-3.0	0.20-0.60
SS-316L	bal	16.0-18.0	10.0-14.0	0-2.0	0-1.0	0-0.03	0-0.03	0-0.045	2.0-3.0	0-0.03
SS-409L[(b)]	bal	10.5-11.75	. . .	0-1.0	0-1.0	0-0.03	0-0.03	0-0.04	. . .	0-0.03
SS-410	bal	11.5-13.5	. . .	0-1.0	0-1.0	0-0.03	0-0.25	0-0.04	. . .	0.20-0.60
SS-410L	bal	11.5-13.5	. . .	0-1.0	0-1.0	0-0.03	0-0.03	0-0.04	. . .	0-0.03
SS-430N2	bal	16.0-18.0	. . .	0-1.0	0-1.0	0-0.03	0-0.08	0-0.04	. . .	0.20-0.60
SS-430L	bal	16.0-18.0	. . .	0-1.0	0-1.0	0-0.03	0-0.03	0-0.04	. . .	0-0.03
SS-434N2	bal	16.0-18.0	. . .	0-1.0	0-1.0	0-0.03	0-0.08	0-0.04	0.75-1.25	0.20-0.60
SS-434L	bal	16.0-18.0	. . .	0-1.0	0-1.0	0-0.03	0-0.03	0-0.04	0.75-1.25	0-0.03

Source: MPIF Standard 35, 1997 Edition

(a) Composition may include other elements (2.0% max) added for specific purposes.

(b) Also includes niobium (8 × %C to 0.80% max).

Mechanical properties of sintered stainless steels are determined by powder characteristics, the sintered density, and the sintering parameters. As with other P/M materials, sintered stainless steels with higher density exhibit higher strength. Higher sintering temperatures and longer sintering times produce more pore rounding and grain growth, both of which impart ductility and impact strength to the part. Low carbon, nitrogen, and oxygen contents also raise ductility. High residual carbon increases strength and hardness. Sintering in lower dew point hydrogen increases densification and ductility. If vacuum sintering is done with optimized additions of graphite, low oxygen contents of 600 to 800 ppm will result in improved ductility and toughness. Figure 2 compares the yield strength and ductility of type 316L stainless steel sintered in DA and H_2. As stated earlier, parts sintered in DA exhibit higher strength and lower ductility than hydrogen-sintered parts. The mechanical properties of vacuum-sintered stainless steels are similar to those of hydrogen-sintered stainless steels. Table 2 lists the mechanical properties of standard (MPIF) austenitic, ferritic, and martensitic grades.

Table 2 Minimum and typical properties of standard (MPIF) P/M stainless steel

Designation(a)	Ultimate tensile strength		0.2% offset yield strength		Elongation in 25 mm (1 in.), %	Unnotched Charpy impact energy		0.1% compressive yield strength		Transverse rupture strength		Apparent Rockwell hardness	Density, g/cm^3
	MPa	**ksi**	**MPa**	**ksi**		**J**	**ft·lbf**	**MPa**	**ksi**	**MPa**	**ksi**		
SS-303N1-25(b)	270	39	220	32	0.5	5	3.5	260	38	590	86	62 HRB	6.4
SS-303N2-35(b)	380	55	290	42	5.0	26	19	320	46	680	99	63 HRB	6.5
SS-303N2-38(b)	470	68	310	45	10.0	47	35	320	46	. . .	. . .	70 HRB	6.9
SS-303L-12(b)	270	39	120	17	17.5	54	40	140	20	570	83	21 HRB	6.6
SS-303L-15(b)	330	48	170	25	20.0	75	55	200	29	. . .	. . .	35 HRB	6.9
SS-304N1-30(b)	300	44	260	38	0.5	5	3.5	260	38	770	112	61 HRB	6.4
SS-304N2-33(b)	390	57	280	41	10.0	34	25	320	46	880	128	62 HRB	6.5
SS-304N2-38(b)	480	70	310	45	13.0	75	55	320	46	. . .	. . .	68 HRB	6.9
SS-304L-13(b)	300	44	120	17	23.0	61	45	150	22	. . .	. . .	30 HRB	6.6
SS-304L-18(b)	390	57	180	26	26.0	108	80	190	28	. . .	. . .	45 HRB	6.9
SS-316N1-25(b)	280	41	230	33	0.5	7	5	250	36	740	107	59 HRB	6.4
SS-316N2-33(b)	410	59	270	39	10.0	38	28	300	44	860	125	62 HRB	6.5
SS-316N2-38(b)	480	70	310	45	13.0	65	48	320	46	. . .	. . .	65 HRB	6.9

SS-316L-15[(b)]	280	41	140	20	18.5	47	35	150	22	550	80	20 HRB	6.6
SS-316L-22[(b)]	390	57	210	30	21.0	88	65	200	29	. . .	. . .	45 HRB	6.9
SS-410-90HT[(c)]	720	104	[(d)]	[(d)]	<0.5	3	2	640	93	780	113	23 HRC[(e)]	6.5
SS-410L-20[(b)]	330	48	180	26	16.0	68	28	190	28	. . .	. . .	45 HRB	6.9
SS-430N2-28[(b)]	410	59	240	35	5.0	34	25	230	33	. . .	. . .	70 HRB	7.1
SS-434L-24[(b)]	340	49	210	30	20.0	108	80	230	33	. . .	. . .	45 HRB	7.1
SS-434N2-28[(b)]	410	59	240	35	8.0	20	15	230	33	. . .	. . .	68 HRB	7.0
SS-434L-24[(b)]	340	49	210	30	15.0	88	65	230	33	. . .	. . .	50 HRB	7.0

Minimum strength values (in ksi) are specified by the numerical suffix in the first column of the table. Typical values are given in the remaining columns.

Source: MPIF Standard 35, 1997 Edition

(a) Codes for the stainless steel designations: N1, nitrogen alloyed with good strength and low elongation, sintered at 1150 °C (2100 °F) in dissociated ammonia; N2, nitrogen alloyed with high strength and medium elongation, sintered at 1290 °C (2350 °F) in dissociated ammonia; L, low carbon with lower strength and highest elongation, sintered at 1290 °C (2350 °F) in partial vacuum, cooled to avoid nitrogen absorption; HT, martensitic grade, sinter hardened at 1150 °C (2100 °F) in dissociated ammonia to highest strength.

(b) The numerical suffix represents the minimum yield strength in ksi.

(c) The numerical suffix represents the ultimate tensile strength in ksi.

(d) Yield and ultimate tensile strength are approximately the same for heat treated materials.

(e) Or a matrix (converted) hardness of 55 HRC.

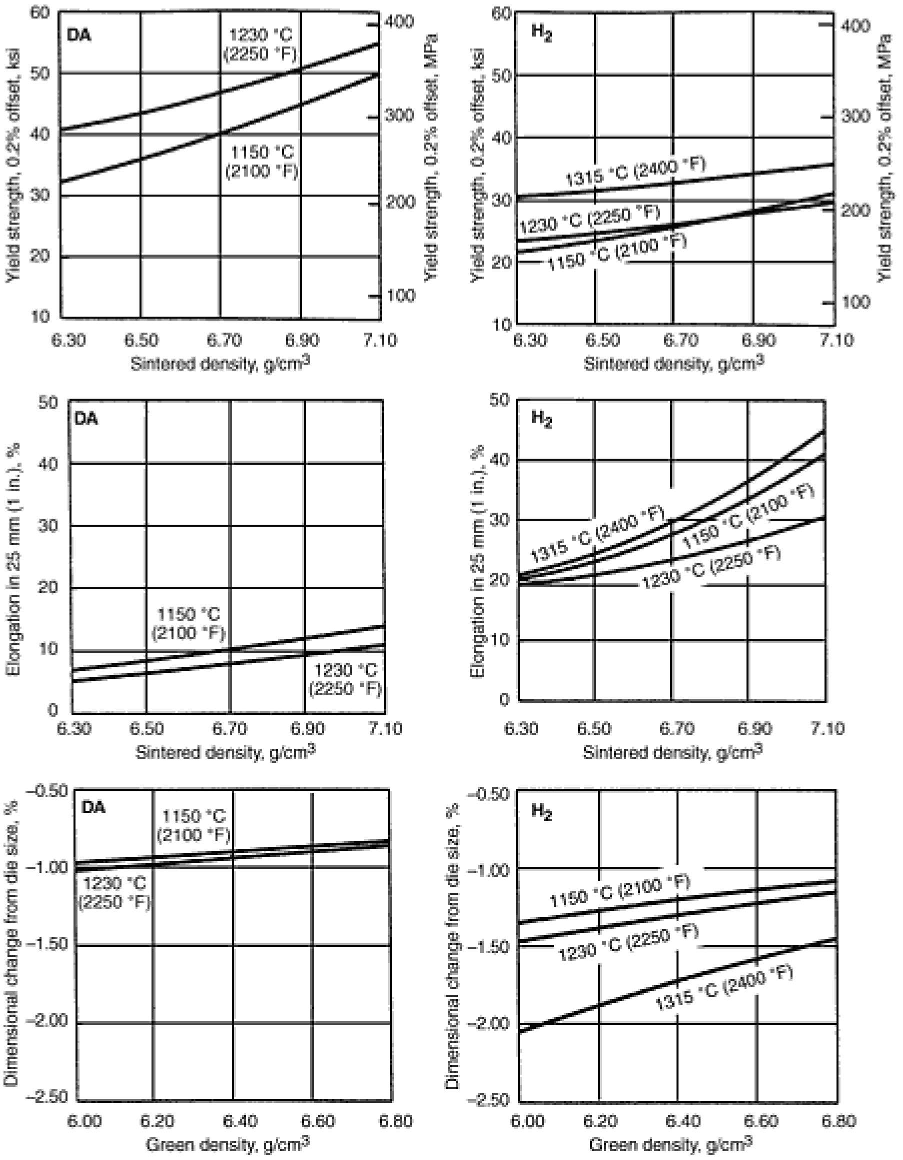

Fig. 2 Comparison of yield strength, ductility, and shrinkage of type 316L austenitic stainless steel compacts sintered in dissociated ammonia (DA) and hydrogen (H_2)

Dimensional Changes. As shown at the bottom of Fig. 2, sintering in hydrogen (or under vacuum), particularly at higher temperatures, produces significant shrinkage, which in turn impairs the dimensional accuracy of the part. For this reason, such parts are often sized after sintering.

Corrosion Resistance. The most frequent processing problems in the P/M stainless steel parts producing industry are related to improper lubrication, excessive dew points in sintering furnaces, slow cooling rates after sintering, and contamination with iron or low-alloy steel powders. Improper delubrication can lead to high residual carbon and/or oxygen contents, which can cause intergranular corrosion and pitting corrosion. Excessive dew points most often result in the oxidation of the surface layers of the sintered parts during cooling. The amount of absorbed oxygen is usually too small to be identified by conventional oxygen analysis or to be noticed as discoloration on the surface. This condition produces low pitting resistance. Slow cooling rates can cause precipitation of carbides at the grain boundaries, in the same manner as sensitization occurs in wrought stainless steels. Slow cooling in nitrogen-bearing atmospheres can lead to absorption of nitrogen on the surface of the part, forming chromium nitrides, which can also impair corrosion resistance. Contamination with less noble metal powders produces galvanic corrosion. Table 3 summarizes the effects of process variables on the corrosion resistance of P/M stainless steels.

Table 3 Effect of iron, carbon, nitrogen, oxygen, and density on the corrosion resistance of sintered austenitic stainless steels in neutral NaCl solution

Variable	Origin of problem	Effect on corrosion resistance	Suggested solutions
Iron	Contamination of prealloyed powder with iron or iron-base powder at powder or parts producer's facility	Lowering of corrosion resistance by more than 99% due to galvanic corrosion	Utmost cleanliness at both powder and parts producer's manufacturing facilities, preferably separate and dedicated equipment and facilities
Carbon	Inadequate lubricant removal; carburizing sintering atmosphere; soot in sintering furnace; high-carbon powder	Inferior resistance to intergranular corrosion	Use L-grade designation of stainless steel powder. Ensure adequate lubricant removal (before sintering). Use clean soot-free sintering furnace and carbon-free sintering atmospheres; carbon content of austenitic sintered parts should be $\leq$0.03% and even lower for ferritics.
Nitrogen	Sintering in dissociated NH_3 or other nitrogen-containing atmosphere combined with slow cooling	Inferior resistance to intergranular corrosion	Reduce percentage of nitrogen in sintering atmosphere. Use fast cooling of parts preferably >150 to 200 °C/min (270 to 360 °F/min) through critical temperature range (700 to 1000 °C, or 1290 to 1830 °F). Use higher sintering temperature. Use intermediate dew points (-37 to -45 °C, or -35 to -50 °F) in cooling zone of furnace. Use tin-modified stainless steel powders.
Oxygen	Excessive oxygen in powder; excessive dew point of sintering atmosphere; slow cooling after sintering	Inferior resistance to general corrosion	Use low-oxygen content powder, preferably <2000 ppm. Control dew point within sintering furnace to ensure reducing conditions. Fast cooling, preferably >200 °C/min (360 °F/min) For nitrogen-containing atmospheres, use dew point of -37 to -45 °C (-35 to -50 °F) in cooling zone. For sintering in H_2, ensure that water vapor content of atmosphere is below 50 ppm.
Density of sintered part	High sintered density	Inferior resistance to crevice corrosion	Avoid sintered densities in the range of approximately 6.7 to 7.4 g/cm^3, or impregnate pores in this density range. In acidic environments, corrosion resistance improves with increasing density due to a decrease of specific surface area.

High-Density P/M Stainless Steels

Fully dense stainless steels are made predominantly by hot isostatic pressing (HIP), cold isostatic pressing (CIP) plus extrusion, and metal injection molding (MIM). The mechanical properties and corrosion resistance of parts produced by these techniques are generally similar to those of their conventional wrought counterparts. Hot isostatically pressed parts include flanges, fitting, valve bodies, and pump components made from duplex stainless steel used for offshore applications. Cold isostatically pressed-and-extruded austenitic stainless steel seamless tubing is also used for offshore applications.

Metal injection molding technology is utilized for high-strength applications where shape complexity is a factor. Stainless steel powders that are most commonly injection molded include austenitic, duplex, and precipitation-hardening grades. Tables 4 and 5 list compositions and properties of standardized injection-molded stainless steels. Applications for injection-molded stainless steels include dental bracket components, disk drive components, firing pins, blades for crimping/cutting tools used for telephone terminal wire connections, and assorted automotive components.

Table 4 Compositions of standard (MPIF) injection-molded stainless steels

MPIF designation	Composition[(a)], wt%							
	Fe	**Ni**	**Cr**	**Mo**	**C**	**Cu**	**Nb + Ta**	**Other[(b)]**
MIM-316L	bal	10.0-14.0	16.0-18.0	2.0-3.0	0.03	. . .	. . .	2.0
MIM-Duplex (316L)	bal	7.5-8.5	19.0-21.0	1.5-2.5	0.03	. . .	. . .	2.0
MIM-17-4 PH	bal	3.0-5.0	15.5-17.5	. . .	0.07	3.0-5.0	0.15-0.45	2.0

Source: MPIF Standard 35, "Materials Standards for Metal Injection Molded Parts" (1993-1994 edition)

(a) Single values are maximum values unless otherwise stated.

(b) Other elements not specified in standard.

Table 5 Minimum and typical properties for standard (MPIF) injection-molded stainless steels

Material designation/condition	Minimum values					Typical values						
	Ultimate strength		**0.2% yield strength**		**Elongation in 25 mm (1 in.), %**	**Ultimate strength**		**0.2% yield strength**		**Elongation in 25 mm (1 in.), %**	**Density, g/cm^3**	**Apparent hardness**
	MPa	**ksi**	**MPa**	**ksi**		**MPa**	**ksi**	**MPa**	**ksi**			
MIM-316L, as-sintered	448	65	138	20	40	517	75	172	25	50	7.6	67 HRB
MIM-Duplex, as-sintered	469	68	179	26	33	538	78	228	33	43	7.6	84 HRB
MIM-17-4 PH, as-sintered	793	115	648	94	4	896	130	731	106	6	7.5	27 HRC
MIM-17-4 PH, solution treated and aged	1069	155	965	140	4	1186	172	1089	158	6	7.5	33 HRC

MIM, metal injection molding. Source: MPIF Standard 35, "Materials Standards for Metal Injection Molded Parts" (1993-1994

Superalloys

Matthew J. Donachie, Rensselaer at Hartford; Stephen J. Donachie, Special Metals Corporation

Introduction

SUPERALLOYS are nickel-, iron-nickel-, and cobalt-base alloys generally used at temperatures above approximately 540 °C (1000 °F). They have a face-centered cubic (fcc, austenitic) structure. Iron, cobalt, and nickel are transition metals with consecutive positions in the periodic table of elements. The iron-nickel-base superalloys are an extension of stainless steel technology and generally are wrought, whereas cobalt-base and nickel-base superalloys may be wrought or cast, depending on the application/composition involved.

Appropriate compositions of all superalloy base metals can be forged, rolled to sheet, or otherwise formed into a variety of shapes. The more highly alloyed compositions normally are processed as castings. Fabricated structures can be built up by welding or brazing, but many highly alloyed compositions containing a high amount of hardening phase are difficult to weld.

Properties can be controlled by adjustments in composition and by processing (including heat treatment), and excellent elevated-temperature strengths are available in finished products. Figure 1 compares stress rupture behavior of the three alloy classes.

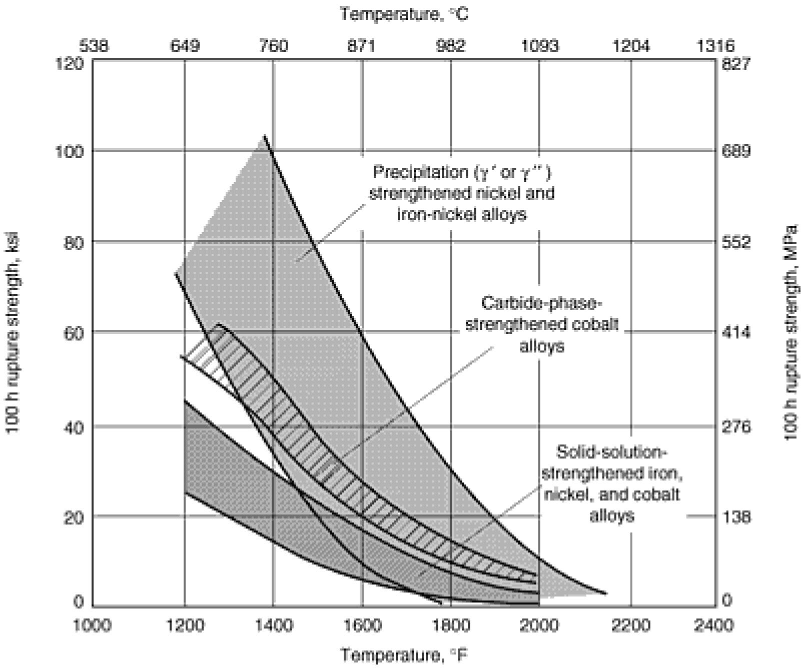

Fig. 1 General stress-rupture behavior of superalloys

General Background

Important Metal Characteristics

Pure iron has a density of 7.87 g/cm^3 (0.284 lb/in.^{3}), and pure nickel and cobalt have densities of approximately 8.9 g/cm^3 (0.322 lb/in.^{3}). Iron-nickel-base superalloys have densities of approximately 7.9 to 8.3 g/cm^3 (0.285 to 0.300 lb/in.^{3}); cobalt-base superalloys, approximately 8.3 to 9.4 g/cm^3 (0.300 to 0.340 lb/in.^{3}); and nickel-base superalloys, approximately 7.8 to 8.9 g/cm^3 (0.282 to 0.322 lb/in.^{3}). Superalloy density is influenced by alloying additions: aluminum, titanium, and chromium reduce density, whereas tungsten, rhenium, and tantalum increase it. The corrosion resistance of superalloys depends primarily on the alloying elements added and the environment experienced.

The melting temperatures of the pure elements are as follows: nickel, 1453 °C (2647 °F); cobalt, 1495 °C (2723 °F); and iron, 1537 °C (2798 °F). Incipient melting temperatures and melting ranges of superalloys are functions of composition and prior processing. Generally, incipient melting temperatures are greater for cobalt-base than for nickel- or iron-nickel-base superalloys. Nickel-base superalloys may show incipient melting at temperatures as low as 1204 °C (2200 °F). Advanced nickel-base single-crystal superalloys with limited amounts of melting-point depressants tend to have incipient melting temperatures equal to or in excess of those of cobalt-base alloys.

Iron and cobalt both undergo allotropic transformations and become fcc at high temperatures; nickel, on the other hand, is fcc at all temperatures. In superalloys based on iron and cobalt, the fcc forms of these elements generally are stabilized by alloying additions. The upper limit of usage for superalloys is not restricted by the occurrence of allotropic transformation reactions, but rather is a function of incipient melting temperature and dissolution of strengthening phases. Some tendency toward transformation of the fcc phase to stable lower-temperature phases occasionally occurs in cobalt-base superalloys. The austenitic fcc matrices of superalloys have extended solubility for some alloying additions, excellent ductility, and favorable characteristics for precipitation of uniquely effective strengthening phases (iron-nickel- and nickel-base superalloys).

Superalloys typically have moduli of elasticity in the vicinity of 207 GPa (30×10^6 psi), although moduli of specific polycrystalline alloys can vary from 172 to 241 GPa (25 to 35×10^6 psi) at room temperature, depending on the alloy system. Processing that leads to directional grain or crystal orientation can result in moduli of approximately 124 to 310 GPa (about 18 to 45×10^6 psi), depending on the relation of grain or crystal orientation to testing direction. Physical properties (electrical conductivity, thermal conductivity, and thermal expansion) tend to be low compared to other metal systems. These properties are influenced by the nature of the base metals (transition elements) and the presence of refractory-metal additions.

The superalloys are relatively ductile, although the ductilities of cobalt-base superalloys generally are less than those of iron-nickel- and nickel-base superalloys. Iron-nickel- and nickel-base superalloys are readily available in extruded, forged, or rolled form; the higher-strength alloys generally are found only in the cast condition. Hot deformation is the preferred forming process, cold forming usually being restricted to thin sections (sheet). Cold rolling may be used to increase short-time strength properties for applications at temperatures below the lower temperature level of 540 °C (1000 °F) established in this article for superalloy use.

Phases and Structures of Superalloys

Superalloys consist of the austenitic fcc matrix phase γ plus a variety of secondary phases. Secondary phases of value in controlling properties are the carbides MC, $M_{23}C_6$, M_6C, and M_7C_3 (rare) in all superalloy types; the γ' fcc ordered $Ni_3(Al,Ti)$, γ'' bct (body-centered tetragonal) ordered Ni_3Nb, η hexagonal ordered Ni_3Ti, and δ orthorhombic Ni_3Nb intermetallic compounds in nickel- and iron-nickel-base superalloys. The superalloys derive their strength from solid-solution hardeners and precipitated phases. Principal strengthening precipitate phases are γ' and γ''. Carbides may provide limited strengthening directly (e.g., through dispersion hardening) or, more commonly, indirectly (e.g., by stabilizing grain boundaries against excessive shear). The δ and η phases are useful (along with γ') in control of structure of wrought superalloys during processing. The extent to which they directly contribute to strengthening depends on the alloy and its processing.

In addition to those elements that produce solid-solution hardening and/or promote carbide and γ' formation, other elements (e.g., boron, zirconium, and hafnium) are added to enhance mechanical or chemical properties. Some carbide- and γ'-forming elements may contribute significantly to chemical properties as well. Tables 1(a) and 1(b), respectively, give a generalized list of the ranges of alloying elements and their effects in superalloys. Typical operating microstructures of representative superalloys are shown in Fig. 2.

Table 1(a) Common ranges of major alloying additions in superalloys

Element	Range, %	
	Fe-Ni- and Ni-base	**Co-base**
Cr	5-25	19-30
Mo, W	0-12	0-11
Al	0-6	0-4.5
Ti	0-6	0-4
Co	0-20	. . .
Ni	. . .	0-22
Nb	0-5	0-4
Ta	0-12	0-9
Re	0-6	0-2

Table 1(b) Role of alloying elements in superalloys

Effect[(a)]	Iron-base	Cobalt-base	Nickel-base
Solid-solution strengtheners	Cr, Mo	Nb, Cr, Mo, Ni, W, Ta	Co, Cr, Fe, Mo, W, Ta, Re
fcc matrix stabilizers	C, W, Ni	Ni	. . .
Carbide form:			
MC	Ti	Ti	W, Ta, Ti, Mo, Nb, Hf
M_7C_3	. . .	Cr	Cr
$M_{23}C_6$	Cr	Cr	Cr, Mo, W
M_6C	Mo	Mo, W	Mo, W, Nb

Carbonitrides: M(CN)	C, N	C, N	C, N
Promotes general precipitation of carbides	P	. . .	. . .
Forms γ' $Ni_3(Al,Ti)$	Al, Ni, Ti	. . .	Al, Ti
Retards formation of hexagonal η(Ni_3Ti)	Al, Zr	. . .	. . .
Raises solvus temperature of γ'	. . .	. . .	Co
Hardening precipitates and/or intermetallics	Al, Ti, Nb	Al, Mo, Ti(b), W, Ta	Al, Ti, Nb
Oxidation resistance	Cr	Al, Cr	Al, Cr, Y, La, Ce
Improve hot corrosion resistance	La, Y	La, Y, Th	La, Th
Sulfidation resistance	Cr	Cr	Cr, Co, Si
Improves creep properties	B	. . .	B, Ta
Increases rupture strength	B	B, Zr	B(c)
Grain-boundary refiners	. . .	. . .	B, C, Zr, Hf
Facilitates working	. . .	Ni_3Ti	. . .
Retard γ' coarsening	. . .	. . .	Re

Source: Adapted from Ref 1

(a) Not all these effects necessarily occur in a given alloy.

(b) Hardening by precipitation of Ni_3Ti also occurs if sufficient Ni is present.

(c) If present in large amounts, borides are formed.

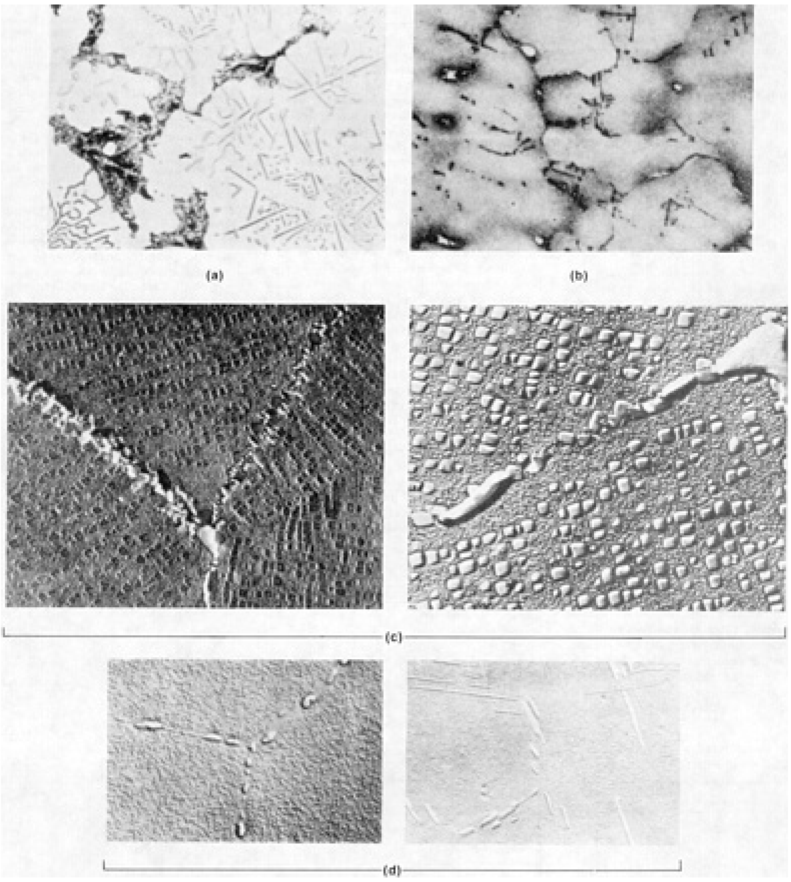

Fig. 2 Typical operating microstructures of representative superalloys. (a) Cast cobalt-base alloy. 250×. (b) Cast nickel-base alloy. 100×. (c) Wrought (left, 3300×) and cast (right, 5000×) nickel-base alloys. (d) Two wrought iron-nickel-base alloys (left, 17,000×; right, 3300×). Note script carbides in (a) and (b) as well as eutectic carbide-cobalt grain-boundary structures in (a), spheroidal and cuboidal γ' as well as grain-boundary carbides in (c), and spheroidal γ' as well as grain-boundary carbides or grain-boundary and intragranular δ phase in (d). γ'' not obvious but present in (d) (right).

Superalloy Systems

The three types of superalloys--iron-nickel-, nickel-, and cobalt-base--may be further subdivided into cast and wrought. A large number of alloys have been invented and studied; many have been patented. However, the many alloys have been winnowed down over the years, and only a few are extensively used. Alloy usage is a function of industry (gas turbines, steam turbines, etc.). Not all alloys can be mentioned; examples of older and newer alloys will be used to demonstrate the physical metallurgy response of superalloy systems. Representative superalloys and compositions emphasizing alloys developed in the United States are listed in Tables 2 and 3.

Table 2 Nominal compositions of wrought superalloys

Alloy	UNS Number	Composition, %										
		Cr	**Ni**	**Co**	**Mo**	**W**	**Nb**	**Ti**	**Al**	**Fe**	**C**	**Other**
Solid-solution alloys												
Iron-nickel-base												
Alloy N-155 (Multimet)	R30155	21.0	20.0	20.0	3.00	2.5	1.0	. . .	. . .	32.2	0.15	0.15 N, 0.2 La, 0.02 Zr
Haynes 556	R30556	22.0	21.0	20.0	3.0	2.5	0.1	. . .	0.3	29.0	0.10	0.50 Ta, 0.02 La, 0.002 Zr
19-9 DL	S63198	19.0	9.0	. . .	1.25	1.25	0.4	0.3	. . .	66.8	0.30	1.10 Mn, 0.60 Si
Incoloy 800	N08800	21.0	32.5	. . .	. . .	. . .	. . .	0.38	0.38	45.7	0.05	. . .
Incoloy 800H	N08810	21.0	33.0	. . .	. . .	. . .	. . .	. . .	. . .	45.8	0.08	. . .
Incoloy 800HT	N08811	21.0	32.5	. . .	. . .	. . .	. . .	0.4	0.4	46.0	0.08	0.8 Mn, 0.5 Si, 0.4 Cu
Incoloy 801	N08801	20.5	32.0	. . .	. . .	. . .	. . .	1.13	. . .	46.3	0.05	. . .
Incoloy 802	. . .	21.0	32.5	. . .	. . .	. . .	. . .	0.75	0.58	44.8	0.35	. . .
Nickel-base												
Haynes 214	. . .	16.0	76.5	. . .	. . .	. . .	. . .	. . .	4.5	3.0	0.03	
Haynes 230	N06230	22.0	55.0	5.0 max	2.0	14.0	. . .	. . .	0.35	3.0 max	0.10	0.015 max B, 0.02 La
Inconel 600	N06600	15.5	76.0	. . .	. . .	. . .	. . .	. . .	. . .	8.0	0.08	0.25 Cu
Inconel 601	N06601	23.0	60.5	. . .	. . .	. . .	. . .	. . .	1.35	14.1	0.05	0.5 Cu
Inconel 617	N06617	22.0	55.0	12.5	9.0	. . .	. . .	. . .	1.0	. . .	0.07	. . .
Inconel 625	N06625	21.5	61.0	. . .	9.0	. . .	3.6	0.2	0.2	2.5	0.05	. . .

RA 333	N06333	25.0	45.0	3.0	3.0	3.0	. . .	. . .	. . .	18.0	0.05	. . .
Hastelloy B	N10001	1.0 max	63.0	2.5 max	28.0	. . .	. . .	. . .	. . .	5.0	0.05 max	0.03 V
Hastelloy N	N10003	7.0	72.0	. . .	16.0	. . .	. . .	0.5 max	. . .	5.0 max	0.06	
Hastelloy S	N06635	15.5	67.0	. . .	15.5	. . .	. . .	. . .	0.2	1.0	0.02 max	0.02 La
Hastelloy W	N10004	5.0	61.0	2.5 max	24.5	. . .	. . .	. . .	. . .	5.5	0.12 max	0.6 V
Hastelloy X	N06002	22.0	49.0	1.5 max	9.0	0.6	. . .	. . .	2.0	15.8	0.15	. . .
Hastelloy C-276	N10276	15.5	59.0	. . .	16.0	3.7	. . .	. . .	. . .	5.0	0.02 max	. . .
Haynes HR-120	N08120	25.0	37.0	3.0	2.5	2.5	0.7	. . .	0.1	33.0	0.05	0.7 Mn, 0.6 Si, 0.2 N, 0.004 B
Haynes HR-160	N12160	28.0	37.0	29.0	. . .	. . .	. . .	. . .	. . .	2.0	0.05	2.75 Si, 0.5 Mn
Nimonic 75	N06075	19.5	75.0	. . .	. . .	. . .	. . .	0.4	0.15	2.5	0.12	0.25 max Cu
Nimonic 86	. . .	25.0	65.0	. . .	10.0	. . .	. . .	. . .	. . .	. . .	0.05	0.03 Ce, 0.015 Mg
Cobalt-base												
Haynes 25 (L605)	R30605	20.0	10.0	50.0	. . .	15.0	. . .	. . .	. . .	3.0	0.10	1.5 Mn
Haynes 188	R30188	22.0	22.0	37.0	. . .	14.5	. . .	. . .	. . .	3.0 max	0.10	0.90 La
Alloy S-816	R30816	20.0	20.0	42.0	4.0	4.0	4.0	. . .	. . .	4.0	0.38	. . .
MP35-N	R30035	20.0	35.0	35.0	10.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .
MP159	R30159	19.0	25.0	36.0	7.0	. . .	0.6	3.0	0.2	9.0	. . .	. . .
Stellite B	N07718	30.0	1.0	61.5	. . .	4.5	. . .	. . .	. . .	1.0	1.0	. . .

UMCo-50	. . .	28.0	. . .	49.0	. . .	. . .	. . .	. . .	. . .	21.0	0.12	. . .
Precipitation-hardening alloys												
Iron-nickel-base												
A-286	S66286	15.0	26.0	. . .	1.25	. . .	. . .	2.0	0.2	55.2	0.04	0.005 B, 0.3 V
Discaloy	S66220	14.0	26.0	. . .	3.0	. . .	. . .	1.7	0.25	55.0	0.06	. . .
Incoloy 903	N19903	0.1 max	38.0	15.0	0.1	. . .	3.0	1.4	0.7	41.0	0.04	. . .
Pyromet CTX-1	. . .	0.1 max	37.7	16.0	0.1	. . .	3.0	1.7	1.0	39.0	0.03	. . .
Incoloy 907	N19907	. . .	38.4	13.0	. . .	. . .	4.7	1.5	0.03	42.0	0.01	0.15 Si
Incoloy 909	N19909	. . .	38.0	13.0	. . .	. . .	4.7	1.5	0.03	42.0	0.01	0.4 Si
Incoloy 925	N09925	20.5	44.0	. . .	2.8	. . .	. . .	2.1	0.2	29	0.01	1.8 Cu
V-57	. . .	14.8	27.0	. . .	1.25	. . .	. . .	3.0	0.25	48.6	0.08 max	0.01 B, 0.5 max V
W-545	S66545	13.5	26.0	. . .	1.5	. . .	. . .	2.85	0.2	55.8	0.08 max	0.05 B
Nickel-base												
Astroloy	N13017	15.0	56.5	15.0	5.25	. . .	. . .	3.5	4.4	<0.3	0.06	0.03 B, 0.06 Zr
Custom Age 625 PLUS	N07716	21.0	61.0	. . .	8.0	. . .	3.4	1.3	0.2	5.0	0.01	. . .
Haynes 242	. . .	8.0	62.5	2.5 max	25.0	. . .	. . .	. . .	0.5 max	2.0 max	0.10 max	0.006 max B
Haynes 263	N07263	20.0	52.0	. . .	6.0	. . .	. . .	2.4	0.6	0.7	0.06	0.6 Mn, 0.4 Si, 0.2 Cu
Haynes R-41	N07041	19.0	52.0	11.0	10.0	. . .	. . .	3.1	1.5	5.0	0.09	0.5 Si, 0.1 Mn, 0.006 B

Inconel 100	N13100	10.0	60.0	15.0	3.0	. . .	. . .	4.7	5.5	<0.6	0.15	1.0 V, 0.06 Zr, 0.015 B
Inconel 102	N06102	15.0	67.0	. . .	2.9	3.0	2.9	0.5	0.5	7.0	0.06	0.005 B, 0.02 Mg, 0.03 Zr
Incoloy 901	N09901	12.5	42.5	. . .	6.0	. . .	. . .	2.7	. . .	36.2	0.10 max	. . .
Inconel 702	N07702	15.5	79.5	. . .	. . .	. . .	. . .	0.6	3.2	1.0	0.05	0.5 Mn, 0.2 Cu, 0.4 Si
Inconel 706	N09706	16.0	41.5	. . .	. . .	. . .	. . .	1.75	0.2	37.5	0.03	2.9 (Nb + Ta), 0.15 max Cu
Inconel 718	N07718	19.0	52.5	. . .	3.0	. . .	5.1	0.9	0.5	18.5	0.08 max	0.15 max Cu
Inconel 721	N07721	16.0	71.0	. . .	. . .	. . .	. . .	3.0	. . .	6.5	0.04	2.2 Mn, 0.1 Cu
Inconel 722	N07722	15.5	75.0	. . .	. . .	. . .	. . .	2.4	0.7	7.0	0.04	0.5 Mn, 0.2 Cu, 0.4 Si
Inconel 725	N07725	21.0	57.0	. . .	8.0	. . .	3.5	1.5	0.35 max	9.0	0.03 max	
Inconel 751	N07751	15.5	72.5	. . .	. . .	. . .	1.0	2.3	1.2	7.0	0.05	0.25 max Cu
Inconel X-750	N07750	15.5	73.0	. . .	. . .	. . .	1.0	2.5	0.7	7.0	0.04	0.25 max Cu
M-252	N07252	19.0	56.5	10.0	10.0	. . .	. . .	2.6	1.0	<0.75	0.15	0.005 B
Nimonic 80A	N07080	19.5	73.0	1.0	. . .	. . .	. . .	2.25	1.4	1.5	0.05	0.10 max Cu
Nimonic 90	N07090	19.5	55.5	18.0	. . .	. . .	. . .	2.4	1.4	1.5	0.06	. . .
Nimonic 95	. . .	19.5	53.5	18.0	. . .	. . .	. . .	2.9	2.0	5.0 max	0.15 max	+B, +Zr
Nimonic 100	. . .	11.0	56.0	20.0	5.0	. . .	. . .	1.5	5.0	2.0 max	0.30 max	+B, +Zr
Nimonic 105	. . .	15.0	54.0	20.0	5.0	. . .	. . .	1.2	4.7	. . .	0.08	0.005 B
Nimonic 115	. . .	15.0	55.0	15.0	4.0	. . .	. . .	4.0	5.0	1.0	0.20	0.04 Zr

C-263	N07263	20.0	51.0	20.0	5.9	. . .	. . .	2.1	0.45	0.7 max	0.06	. . .
Pyromet 860	. . .	13.0	44.0	4.0	6.0	. . .	. . .	3.0	1.0	28.9	0.05	0.01 B
Pyromet 31	N07031	22.7	55.5	. . .	2.0	. . .	1.1	2.5	1.5	14.5	0.04	0.005 B
Refractaloy 26	. . .	18.0	38.0	20.0	3.2	. . .	. . .	2.6	0.2	16.0	0.03	0.015 B
René 41	N07041	19.0	55.0	11.0	10.0	. . .	. . .	3.1	1.5	<0.3	0.09	0.01 B
René 95	. . .	14.0	61.0	8.0	3.5	3.5	3.5	2.5	3.5	<0.3	0.16	0.01 B, 0.05 Zr
René 100	. . .	9.5	61.0	15.0	3.0	. . .	. . .	4.2	5.5	1.0 max	0.16	0.015 B, 0.06 Zr, 1.0 V
Udimet 500	N07500	19.0	48.0	19.0	4.0	. . .	. . .	3.0	3.0	4.0 max	0.08	0.005 B
Udimet 520	. . .	19.0	57.0	12.0	6.0	1.0	. . .	3.0	2.0	. . .	0.08	0.005 B
Udimet 630	. . .	17.0	50.0	. . .	3.0	3.0	6.5	1.0	0.7	18.0	0.04	0.004 B
Udimet 700	. . .	15.0	53.0	18.5	5.0	. . .	. . .	3.4	4.3	<1.0	0.07	0.03 B
Udimet 710	. . .	18.0	55.0	14.8	3.0	1.5	. . .	5.0	2.5	. . .	0.07	0.01 B
Unitemp AF2-1DA	N07012	12.0	59.0	10.0	3.0	6.0	. . .	3.0	4.6	<0.5	0.35	1.5 Ta, 0.015 B, 0.1 Zr
Waspaloy	N07001	19.5	57.0	13.5	4.3	. . .	. . .	3.0	1.4	2.0 max	0.07	0.006 B, 0.09 Zr

Table 3 Nominal compositions of cast superalloys

Alloy designation	Nominal composition, %												
	C	**Ni**	**Cr**	**Co**	**Mo**	**Fe**	**Al**	**B**	**Ti**	**Ta**	**W**	**Zr**	**Other**
Nickel-base													
B-1900	0.1	64	8	10	6	. . .	6	0.015	1	4(a)	. . .	0.10	. . .

CMSX-2	. . .	66.2	8	4.6	0.6	. . .	56	. . .	1	6	8	6	. . .
Hastelloy X	0.1	50	21	1	9	18	. . .	. . .	. . .	. . .	1	. . .	. . .
Inconel 100	0.18	60.5	10	15	3	. . .	5.5	0.01	5	. . .	. . .	0.06	1 V
Inconel 713C	0.12	74	12.5	. . .	4.2	. . .	6	0.012	0.8	1.75	. . .	0.1	0.9 Nb
Inconel 713LC	0.05	75	12	. . .	4.5	. . .	6	0.01	0.6	4	. . .	0.1	. . .
Inconel 738	0.17	61.5	16	8.5	1.75	. . .	3.4	0.01	3.4	. . .	2.6	0.1	2 Nb
Inconel 792	0.2	60	13	9	2.0	. . .	3.2	0.02	4.2	. . .	4	0.1	2 Nb
Inconel 718	0.04	53	19	. . .	3	18	0.5	. . .	0.9	. . .	. . .	. . .	0.1 Cu, 5 Nb
X-750	0.04	73	15	. . .	. . .	7	0.7	. . .	2.5	. . .	. . .	. . .	0.25 Cu, 0.9 Nb
M-252	0.15	56	20	10	10	. . .	1	0.005	2.6	. . .	. . .	. . .	. . .
MAR-M 200	0.15	59	9	10	. . .	1	5	0.015	2	. . .	12.5	0.05	1 Nb(b)
MAR-M 246	0.15	60	9	10	2.5	. . .	5.5	0.015	1.5	1.5	10	0.05	. . .
MAR-M 247	0.15	59	8.25	10	0.7	0.5	5.5	0.015	1	3	10	0.05	1.5 Hf
PWA 1480	. . .	bal	10	5.0	. . .	. . .	5.0	. . .	1.5	12	4.0	. . .	. . .
René 41	0.09	55	19	11.0	10.0	. . .	1.5	0.01	3.1	. . .	. . .	. . .	. . .
René 77	0.07	58	15	15	4.2	. . .	4.3	0.015	3.3	. . .	. . .	0.04	. . .
René 80	0.17	60	14	9.5	4	. . .	3	0.015	5	. . .	4	0.03	. . .
René 80 Hf	0.08	60	14	9.5	4	. . .	3	0.015	4.8	. . .	4	0.02	0.75 Hf
René 100	0.18	61	9.5	15	3	. . .	5.5	0.015	4.2	. . .	. . .	0.06	1V
René N4	0.06	62	9.8	7.5	1.5	. . .	4.2	0.004	3.5	4.8	6	. . .	0.5 Nb, 0.15 Hf
Udimet 500	0.1	53	18	17	4	2	3	. . .	3	. . .	. . .	. . .	. . .

Udimet 700	0.1	53.5	15	18.5	5.25	. . .	4.25	0.03	3.5	. . .	. . .	. . .	. . .
Udimet 710	0.13	55	18	15	3	. . .	2.5	. . .	5	. . .	1.5	0.08	. . .
Waspaloy	0.07	57.5	19.5	13.5	4.2	1	1.2	0.005	3	. . .	. . .	0.09	. . .
WAX-20 (DS)	0.20	72	. . .	. . .	. . .	. . .	6.5	. . .	. . .	. . .	20	1.5	. . .
Cobalt-base													
AiResist 13	0.45	. . .	21	62	. . .	. . .	3.4	. . .	. . .	2	11	. . .	0.1 Y
AiResist 213	0.20	0.5	20	64	. . .	0.5	3.5	. . .	. . .	6.5	4.5	0.1	0.1 Y
AiResist 215	0.35	0.5	19	63	. . .	0.5	4.3	. . .	. . .	7.5	4.5	0.1	0.1 Y
FSX-414	0.25	10	29	52.5	. . .	1	. . .	0.010	. . .	. . .	7.5	. . .	. . .
Haynes 21	0.25	3	27	64	. . .	1	. . .	. . .	. . .	. . .	. . .	. . .	5 Mo
Haynes 25; L-605	0.1	10	20	54	. . .	1	. . .	. . .	. . .	. . .	15	. . .	. . .
J-1650	0.20	27	19	36	. . .	. . .	. . .	0.02	3.8	2	12	. . .	. . .
MAR-M 302	0.85	. . .	21.5	58	. . .	0.5	. . .	0.005	. . .	9	10	0.2	. . .
MAR-M 322	1.0	. . .	21.5	60.5	. . .	0.5	. . .	. . .	0.75	4.5	9	2	. . .
MAR-M 509	0.6	10	23.5	54.5	. . .	. . .	. . .	. . .	0.2	3.5	7	0.5	. . .
MAR-M 918	0.05	20	20	52	. . .	. . .	. . .	. . .	. . .	7.5	. . .	0.1	. . .
NASA Co-W-Re	0.40	. . .	3	67.5	. . .	. . .	. . .	. . .	1	. . .	25	1	2 Re
S-816	0.4	20	20	42	. . .	4	. . .	. . .	. . .	. . .	4	. . .	4 Mo, 4 Nb, 1.2 Mn, 0.4 Si
V-36	0.27	20	25	42	. . .	3	. . .	. . .	. . .	. . .	2	. . .	4 Mo, 2 Nb, 1 Mn, 0.4 Si
WI-52	0.45	. . .	21	63.5	. . .	2	. . .	. . .	. . .	. . .	11	. . .	2 Nb + Ta

X-40 (Stellite alloy 31)	0.50	10	22	57.5	. . .	1.5	. . .	. . .	. . .	. . .	7.5	. . .	0.5 Mn, 0.5 Si

(a) B-1900 + Hf also contains 1.5% Hf.

(b) MAR-M 200 + Hf also contains 1.5% Hf.

Iron-Nickel-Base. The most important class of iron-nickel-base superalloys includes those strengthened by intermetallic compound precipitation in an fcc matrix. The most common precipitate is γ', typified by A-286, V-57, or Incoloy 901. Some alloys, typified by Inconel (IN) 718, which precipitate γ'', were formerly classed as iron-nickel-base but now are considered to be nickel-base. Other iron-nickel-base superalloys consist of modified stainless steels primarily strengthened by solid-solution hardening. Alloys in this last category vary from 19-9DL (18-8 stainless with slight chromium and nickel adjustments, additional solution hardeners, and higher carbon) to Incoloy 800H (21 chromium, high nickel with small additions of titanium and aluminum, which yields some γ' phase).

Nickel-Base. The most important class of nickel-base superalloys is that strengthened by intermetallic-compound precipitation in an fcc matrix. For nickel-titanium/aluminum alloys the strengthening precipitate is γ'. Such alloys are typified by the wrought alloys Waspaloy and Udimet (U) 720, or by the cast alloys René 80 and IN 713. For nickel-niobium alloys the strengthening precipitate is γ''. These alloys are typified by IN 718. Some nickel-base alloys may contain both niobium plus titanium and/or aluminum and utilize both γ' and γ'' precipitates in strengthening. Alloys of this type are IN 706 and IN 909. Another class of nickel-base superalloys is essentially solid-solution strengthened. Such alloys are Hastelloy X and IN 625. The solid-solution strengthened nickel-base alloys may derive some additional strengthening from carbide and/or intermetallic-compound precipitation. A third class includes oxide-dispersion strengthened (ODS) alloys such as IN MA-754 and IN MA-6000E, which are strengthened by dispersion of inert particles such as yttria, coupled in some cases with γ' precipitation (MA 6000E).

Nickel-base superalloys are utilized in both cast and wrought forms, although special processing (powder metallurgy/isothermal forging) is frequently used to produce wrought versions of the more highly alloyed compositions (René 95, Astroloy, IN 100). An additional dimension of nickel-base superalloys has been the introduction of grain-aspect ratio and orientation as a means of controlling properties. In some instances, in fact, grain boundaries have been removed (see the subsequent discussion of investment casting). Wrought powder metallurgy (P/M) alloys of the ODS class and cast alloys such as MAR-M 247 have demonstrated property improvements owing to control of grain morphology by directional recrystallization or solidification.

Cobalt-Base. The cobalt-base superalloys are invariably strengthened by a combination of carbides and solid-solution hardeners. The essential distinction in these alloys is between cast and wrought structures. Cast alloys are typified by X-40 and wrought alloys by L605. No intermetallic compound possessing the same degree of utility as the γ' precipitate in nickel- or iron-nickel-base superalloys has been found to be operative in cobalt-base systems.

Applications

Superalloys have been used in cast, rolled, extruded, forged, and powder-processed forms. Sheet, bar, plate, tubing, shafts, airfoils, disks, and pressure vessels (cases) are some of the shapes that have been produced. These metals have been used in aircraft, industrial, and marine gas turbines; nuclear reactors; aircraft skins; spacecraft structures; petrochemical production; orthopedic and dental prostheses; and environmental protection applications. Although developed for high-temperature use, some are used at cryogenic temperatures and others at body temperature. Applications continue to expand but at lower rates than in previous decades. Aerospace usage remains the predominant application on a volume basis.

Reference cited in this section

1. G.E. Maurer, Primary and Secondary Melt Processing--Superalloys, *Superalloys, Supercomposites and Superceramics,* Academic Press, 1989, p 49-97

Processing

Primary and Secondary Melting

A number of superalloys, particularly cobalt- and iron-nickel-base alloys, are air melted by various methods applicable to stainless steels. However, for most nickel- or iron-nickel-base superalloys, vacuum induction melting (VIM) is required as the primary melting process.

Vacuum induction melting consists of melting the required components of an alloy under high vacuum and pouring into an ingot or article mold. The use of VIM reduces interstitial gases to low levels, enables higher and more reproducible levels of aluminum and titanium (along with other relatively reactive elements) to be achieved, and results in less contamination from slag or dross formation than air melting. The benefits of reduced gas content and ability to control aluminum plus titanium are shown in Fig. 3 and 4.

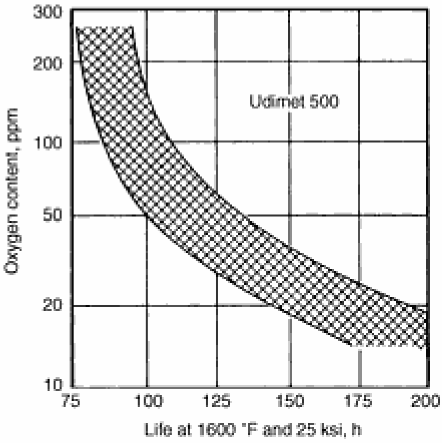

Fig. 3 Improvement of rupture life at 870 °C (1600 °F) and 170 MPa (25 ksi) by reduced oxygen content produced by vacuum melting

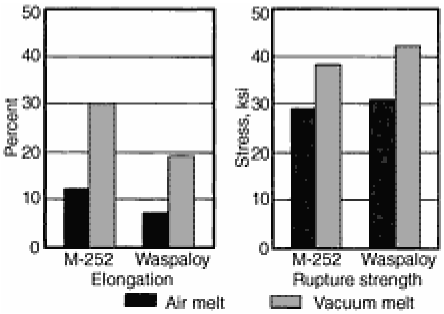

Fig. 4 Effects of vacuum melting, incorporating beneficial modifications in composition, on properties of two nickel-base superalloys

Segregation (on a microscale) occurs during the solidification of all superalloys. The solidification region consists of a zone where the alloy is partially solid and partially liquid (the liquid + solid zone). The solidification mode is generally dendritic and the first (primary) dendrites to form are lower in precipitate-forming elements (titanium, aluminum, niobium, and carbon) than the average melt composition. The interdendritic areas are correspondingly enriched in these solute elements. As cooling rates become slower (increasing casting size), the primary dendrites and interdendritic regions become larger. The slower the cooling rate and the more highly alloyed the melt, the larger the interdendritic regions. At some point, the interdendritic regions become large enough to interconnect and form macroscale defects. Driven by density differences between the solute-rich interdendritic liquid and the nominal melt composition, these regions become self-perpetuating continuous channels in the solidification structure. Such channel defects may grow vertically (but not truly perpendicular) from the solidification front for low-density interdendritic fluids or may grow horizontally (parallel) to the solidification front for high-density interdendritic liquids.

Solute-rich channel defects are referred to as "freckles" because, when viewed in a cross section perpendicular to their growth axis, they are seen as round, dark, circular spots. Freckle regions may form hard intermetallic compounds that cannot be removed by subsequent processing. The presence of such compounds in wrought alloys is extremely detrimental to fatigue life. If the large ingot sizes required for production of wrought alloys are direct static cast, the formation of unacceptable solute-rich defects is essentially unavoidable. Superalloys for wrought production are thus generally remelted (secondary melting) to control the solidification structure. Three types of secondary melting practices are in use: vacuum arc remelting (VAR), electroslag remelting (ESR), and ESR-VAR.

The vacuum arc remelting process utilizes a cast (generally VIM) electrode as the cathode in a direct-current (dc) system. Under vacuum, in a water-cooled crucible, an arc is struck between the electrode and the bottom of the crucible. The heat of the arc melts the bottom surface of the electrode at a controlled rate. The molten metal is resolidified in the crucible, with the electrode melt rate being controlled by the applied power. The melting/solidification parameters control the depth and angle of the solidification front (pool shape). Pool shape can be maintained such that unacceptable solute-rich solidification structures do not occur.

In addition to establishing a controlled solidification structure, VAR reduces the amounts of high-vapor-pressure elements in the alloy. Elements such as bismuth and lead (which can be present in low concentrations even after VIM) are highly undesirable, but are reduced to negligible levels by the VAR process. Magnesium, which is considered desirable for improved workability (and is an addition element in VIM), is reduced in concentration but not completely removed. With the exception of high-vapor-pressure elements, the VIM chemistry is representative of the VAR chemistry. The flotation of oxides and nitrides to the melt surface in VAR improves the cleanliness and reduces the gas content of material processed through VAR.

Figure 5 schematically illustrates the relationship between the VAR electrode, the solidifying ingot, and the shape and depth of the solidification front. In VAR, the first metal to solidify against the water-cooled crucible has low solute content (solute lean). The upper part of this solidification layer is built up of splash from the melt pool and is called the "crown." After the crown is melted back by the advancing molten metal front, an alloy-lean layer remains on the outside of the ingot. This is called "shelf." During the remelting operation, the residual oxides/nitrides in the VIM electrode are swept across the top of the molten pool and incorporated into the shelf.

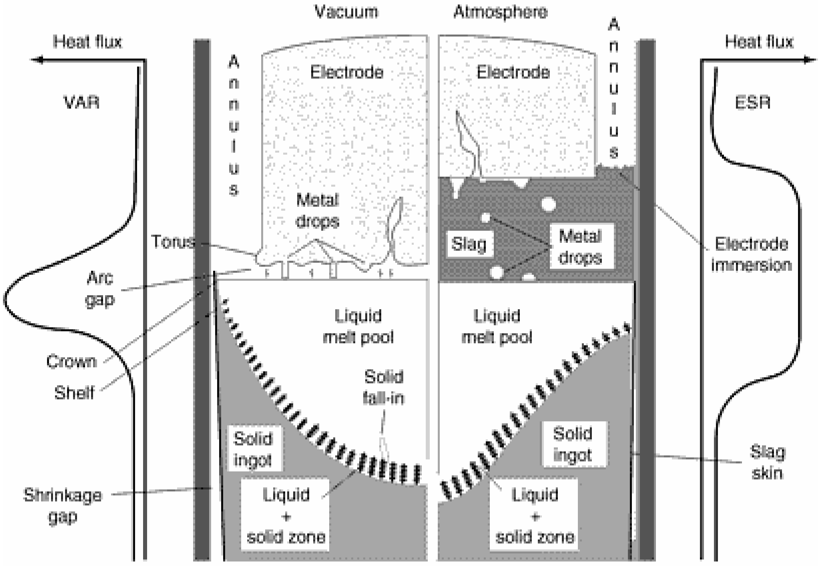

Fig. 5 Schematic of solidification relationships in VAR (left) and ESR (right) melting processes. Source: After

Ref 1

Other important variables of the VAR process are illustrated in Fig. 5. The distance between the side of the electrode and the crucible wall is the annulus. The distance between the bottom of the electrode and the top of the molten pool is the arc gap. As the ingot solidifies, a shrinkage gap is opened between the ingot and the water-cooled crucible. For segregation-sensitive alloys, helium gas is often introduced into the shrinkage gap to improve heat transfer and thus minimize the depth of the molten pool. As shown in Fig. 5, the heat extraction in VAR is concentrated near the top of the molten pool. Vacuum arc remelting is thus a process with low thermal inertia in which very rapid responses (change in pool shape) occur in response to changes in power input.

Freckles, although the most serious defect to occur in secondary melting, are not the only melt-related defect that can be produced. Solute-lean segregation can occur from a number of different sources. The most common mechanism for formation of solute-lean segregation is the undercutting (by the arc) of the shelf, causing a "drop-in" defect. Pieces of the shelf dropping into the pool may not be completely remelted. The result is the incorporation into the structure of a defect with the chemistry of the shelf and which may also contain oxide/nitride stringers. These solute-lean regions are often detected by macroetching of parts/test wafers, where they are seen as light-etching regions in a dark-etching matrix. Thus, they are described as "discrete white spots."

Discrete white spots may also form from drop-in of dendrites from porous regions of the electrode. If the electrode is cracked, pieces larger than dendrites may drop into the melt. While this also produces a light-etching defect, the defect is larger than a discrete white spot and contains dark-etching regions (remnant cast structure). Such structures are often called "dendritic white spots." Although VAR practice and control may be optimized to minimize the frequency of discrete white spot formation, due to the inherent instability of the arc discrete white spots cannot be eliminated. Design of components from VAR-processed material must take into consideration the historical frequency of white spot occurrence for a given process or alloy.

Control of the VAR process is considered from two different aspects: control of pool depth and shape (control of solidification structure) and control of arc stability (control of drop-in defect formation). Pool shape and depth are controlled by regulating heat input and heat extraction. Heat input is determined by the melt rate of the electrode. Melt rate is often monitored and corrected over very short time periods by changes in melt current (melt rate control). Alternatively, control of the median melt rate over the duration of a melt may be maintained by operating at constant melt amperage (amperage control). Heat extraction is a function of the contact surface/ingot volume (ingot size) being melted. Larger ingots have poorer heat extraction (lower surface/volume) and must be melted at proportionately lower melt rates to prevent the formation of large liquid + solid zones and thus the formation of unacceptable positive segregation. While, for a given ingot size, high melt rate may promote positive segregation, a melt rate that is too low may cause the formation of visible solute-lean structures. The mechanism of formation of these "solidification white spots" is not completely understood. They differ from discrete white spots in that they are a solidification effect, not a shelf or electrode drop-in, and therefore do not contain oxide/nitride stringers. Nevertheless, such solute-lean regions are potentially detrimental as they may make it difficult to control grain growth in subsequent processing.

Active control of arc stability is primarily by control of the arc gap throughout the melting of an electrode. (Annulus is a fixed parameter for a given standard process.) For melting of superalloys, arc gaps are generally controlled in the range of 6.4 to 12.7 mm ($\frac{1}{4}$ to $\frac{1}{2}$ in.). To maintain constant arc gap, the electrode is fed into the melt either faster or slower (ram drive) according to the fluctuation in voltage that occurs when the resistance of the system changes in response to changes in the arc gap. Modern control systems for superalloys generally do not use voltage for arc gap control, but rather use a related voltage measurement: the drip short frequency (DSF). A drip short is the transient downward voltage spike that occurs when a molten metal droplet is in contact with both the electrode and the molten pool. The number of shorts occurring in a given time period is proportional to the arc gap. (The relationship for arc gap versus DSF is not melt rate independent.) Passive control of arc stability is maintained by controlling the annulus and controlling the quality of the electrode being remelted. Electrodes for VIM generally contain porosity and low levels of residual refractory, both of which may act to destabilize the arc. Vacuum induction melting and pouring practice is thus a significant factor in ensuring VAR arc stability and in minimizing the formation of drop-in type defects.

The electroslag remelting process, as applied to superalloys, utilizes a cast (generally VIM) electrode as a consumable element in an alternating-current (ac) system operated open to the atmosphere. A "slag" charge of fluorides and oxides is also part of the system and is kept in a molten state by the passage of electric current through it. The electrode is immersed in the slag and the surface of the electrode melts as droplets, which pass through the slag to solidify (similarly to VAR) in a water-cooled crucible. The melt rate is controlled by the applied power. Heat extraction is controlled by the selection of ingot size. By balancing the melting/solidification parameters, the depth and angle of the liquid + solid zone can be maintained such that unacceptable solute-rich solidification defects do not occur.

Unlike VAR, high-vapor-pressure tramp elements are not removed by ESR. Thus, magnesium may be retained at higher levels than is possible in VAR (with beneficial effects on hot workability). A beneficial chemical reaction related to workability is the removal of sulfur. Detrimental compositional changes may occur in reactive elements (notably titanium and aluminum), as these elements change to attain chemical equilibrium with components of the slag.

Oxides incorporated in the electrode being melted are effectively removed by the ESR process, producing an ingot that is generally cleaner than a VAR ingot. The structures in the solidified ingot are governed by the same principles as those governing a solidifying VAR ingot, but the nature of the heat transfer (through an oxide skin) and the presence of a heat reservoir (the molten slag) at the top of the ingot/molten pool make ESR structure inherently different from that of VAR.

Figure 5 schematically illustrates the relationship between the ESR electrode, the solidifying ingot, and the shape and depth of the molten pool. A major feature of ESR solidification is that a "skin" of oxide is incorporated between the ingot surface and the crucible wall. Similar to VAR, the distance between the side of the electrode and the crucible wall is called the annulus. The depth of the slag pool is an important operating parameter which controls the electrical resistance of the system. The depth of immersion of the electrode into the slag is an important parameter in controlling the molten pool shape. As shown in Fig. 5, the heat extraction in ESR is of a much greater magnitude than for VAR. Due to the insulating characteristic of the ingot slag skin, heat extraction in ESR is inherently less efficient than in VAR. Thus, ESR is a process with high thermal inertia, and slow responses (change in pool shape) that occur in response to changes in power input.

The presence of an ingot slag skin not only improves the ingot surface quality but also, more importantly, eliminates the presence of a solute-lean shelf layer on ESR ingots. (As oxide particles from the electrode are dissolved into the slag, they do not agglomerate on the ingot surface.) Because ESR ingots do not have ingot shelf, they are inherently free of the formation of drop-in (discrete) white spots from this source, but drop-in electrode may still be a source of white spots in ESR. Solidification white spots have not been reported in ESR product. However, one consequence of the ingot slag skin is that heat extraction in ESR is less efficient than for VAR. This is shown schematically in Fig. 5 by the difference in pool shape between the two processes. ESR pools tend to be both deeper and more V shaped (compared to a U-shaped VAR pool). Deep pools favor freckle formation, which can only be counteracted by reducing ingot size. Consequently, the maximum size of ESR ingot produced (for any given alloy system) is smaller than one that can be produced by VAR.

Control of the ESR process is considered from two different aspects: control of pool depth and shape (control of solidification structure) and development of a satisfactory ingot skin. Pool depth and shape are controlled primarily by melt rate (power input). Electroslag remelting generally is run using melt rate control, with continuous amperage adjustments to maintain a uniform melt rate. Due to the high thermal inertia of the ESR process, the melt rate of ESR is more variable than in VAR. A secondary control of pool depth and shape is effected by maintaining uniform, shallow immersion of the electrode in the slag. The passage of molten metal droplets through the slag affects slag resistivity and thus causes variation in the operating voltage of the system. The operating voltage appears as a band of values due to this variation. The width of that band is called the volt swing. The electrode immersion is proportional to the volt swing, and the ram drive of the ESR advances the electrode to maintain the desired swing value.

Production of satisfactory ingot skin is not actively controlled during the melt, but is due to the choice of variables. The most important of these are melt rate, depth of the slag pool, and choice of slag composition. Higher melt rates produce better ingot surfaces. As higher melt rates also produce deeper molten pools and move the process closer to the conditions for freckle formation, selection of the correct balance of parameters is critical.

Slag compositions are based on CaF_2. Additions of CaO, MgO, and Al_2O_3 are made to modify both the resistance of the slag and its melting point. All commercial-purity CaF_2 contains SiO_2. During melting of titanium bearing alloys, an exchange will take place between the titanium in the alloy and the silicon in the slag. The slag becomes enriched with TiO_2 and the silicon content of the alloy increases until an equilibrium is established, usually within the first few hundred pounds of melting. To minimize this exchange some commercial slags are buffered with intentional additions of TiO_2.

ESR-VAR Remelting Process. Comparison of the VAR and ESR processes shows that the ESR process is inherently capable of producing cleaner metal but that the VAR process has the capability to produce larger ingots while retaining freedom from alloy-rich defects. The need to produce larger forging stock for gas turbine components has led to the development of a hybrid process: VIM-ESR-VAR (triple melt). In this process, the ESR operation produces a clean, sound electrode for subsequent remelting. The improved (compared to VIM-VAR) electrode quality facilitates control in the VAR operation, producing material with a greater assurance of freedom from alloy-rich segregation (in very large ingot) and a reduced frequency of white spots for all ingot sizes.

In some advanced nickel-base superalloys with high volume fractions (V_f) of γ', even VIM-VAR or VIM-ESR does not provide a satisfactory ingot structure for subsequent hot working. Such superalloys have been processed by P/M techniques (see the section "Powder Processing" in this article).

Other Melting Processes. Electron-beam remelting/refining (EBR) has been evaluated as an alternative process for improving nickel- and iron-nickel-base superalloy properties and processibility through a further lowering of impurity levels and drastic reductions in dross/inclusion content. This process can help produce improved feedstock for casting operations or provide more workable starting ingot for wrought processing. The expanded use of secondary melt processes such as EBR and argon-oxygen decarburization (AOD) will be governed by the extent to which they each provide an economical means for quality processing of nickel- and iron-nickel-base superalloys.

Cobalt Alloy Melting. Melting of cobalt-base superalloys generally does not require the sophistication of vacuum processing. An air induction melt (AIM) is commonly used, but VIM and ESR also have found application, the latter being used to produce stock for subsequent deformation processing. Alloys containing aluminum or titanium (J-1570) and tantalum or zirconium (MAR-M 302 and MAR-M 509) must be melted by VIM. Vacuum melting of other cobalt-base superalloys may enhance properties such as strength and ductility because of the improved cleanness and compositional control associated with this process.

Deformation Processing (Conversion)

As noted in the preceding section, the structure of superalloy ingots consists of primary dendrites, which are solute lean, and interdendritic regions, which are solute rich. For those alloys with sufficient aluminum, titanium, or niobium to exhibit commercially useful age-hardening response, it is necessary to thermally treat the ingot prior to deformation processing. The thermal treatment is referred to as "homogenization" and consists of extended exposure (48 h is not uncommon) to temperatures approaching the incipient melting temperature of the alloy. The degree of segregation which must be removed by homogenization is a function of alloy composition and melt practice. While homogenization treatments are generally effective in producing a great leveling of microscale concentration differences in superalloys, some residual minor differences may remain in areas of large primary dendrite formation.

Consumably remelted superalloys generally are processed to either forged parts or to sheet/plate. Forged products are produced through an intermediate (billet) forging process, during which refinement of the cast structure is accomplished and a recrystallized grain size is established. Subsequent die forging of increments cut from the billet may further refine the structure or may simply shape the increment into the desired form while retaining the billet structure.

Similarly, ingots to be processed into sheet are often converted by cogging to the desired input size for the rolling mill. The large reductions of the subsequent sheet rolling process reduce the need for control of cogged structure compared to that required for forging stock. Thus, for some alloys utilizing ESR as the secondary melt process, the ingot may be "cast" into a slab for direct input into the rolling process.

Workability is affected primarily by composition and secondarily by microstructure. Optimum strain and temperature conditions for working of superalloys can be defined by "processing maps." In superalloys, high sulfur levels may constrict the favorable processing range, while additional elements such as magnesium may counteract the effect of sulfur and expand the process range. Unfavorable microstructure may be formed on grain boundaries at any stage in the processing. An example of carbide films developed on prior-grain boundaries is shown in Fig. 6. Such structures will restrict the range of processing conditions. Some superalloys and their nominal forging temperatures are given in Table 4. Superalloys such as IN 100 may have forging temperatures that vary depending on whether isothermal/superplastic forging is used. Grain refinement requirements also may affect the forging process.

Table 4 Forgeability ratings of superalloys

Alloy	Forging temperature		Forgeability
	°C	**°F**	
A-286	1065	1950	Excellent
Inconel 901	1095	2000	Good to excellent
Hastelloy X	1095	2000	Excellent
Waspaloy	1080	1975	Good
Inconel 718	1065	1950	Excellent
Astroloy	1095	2000	Fair to good

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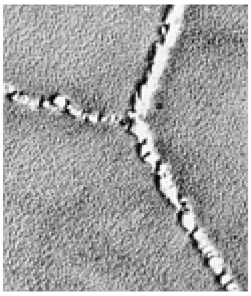

Fig. 6 Continuous or nearly continuous MC film produced in grain boundaries of Waspaloy after high-temperature forging soak with no subsequent reduction, followed by normal solution treating and aging. 2700×

To refine grain structure (to improve low-cycle fatigue resistance and/or stress-rupture resistance) in forgings, it is common to process precipitation-hardening superalloys within a more restricted temperature range than is given in Table 4. The temperature range is restricted so that not all the precipitating elements are in solution during forging, thus causing pinning of grain boundaries and restriction of grain growth. The forging conditions must be chosen and controlled so that sufficient strain and temperature are used to allow recrystallization while not allowing the temperature to exceed the solution temperature for the precipitate. The grain structure obtained by such processing must be retained during heat treatment of the forging by either direct aging of the forged structure or aging after a "pseudo" solution heat treatment that does not exceed the true solution temperature of all the precipitate.

A principal use of such processing is in the production of direct-aged IN 718. Figure 7 shows a time-temperature-transformation (TTT) diagram for the precipitates in IN 718. Note that the TTT diagram does not address the relative volume of each precipitate. In IN 718 the volumes of γ" and δgreatly exceed the volume of γ'. At low temperatures, the metastable precipitates γ' and γ" predominate. At temperatures above 925 °C (1700 °F), the dominant phase is δ. At temperatures around 925 °C (1700 °F), the δphase forms in a needlelike Widmanstätten structure. As the temperature is increased, the morphology of the δphase becomes more blocky. When δphase is subjected to strain at higher temperatures (980 to 1010 °C, or 1800 to 1850 °F), the δphase is spheroidized. As the temperature is increased, the volume of stable precipitate is decreased, with complete solution occurring at the δsolvus temperature. Thus, hot working in the range from 980 to 1010 °C (1800 to 1850 °F) causes the formation of a small volume of spheroidized δphase, which pins grain-boundary growth. The greater percentage of niobium is retained in solution and is available to form the strengthening γ'' precipitate upon subsequent direct heat treatment (aging) of the forged part.

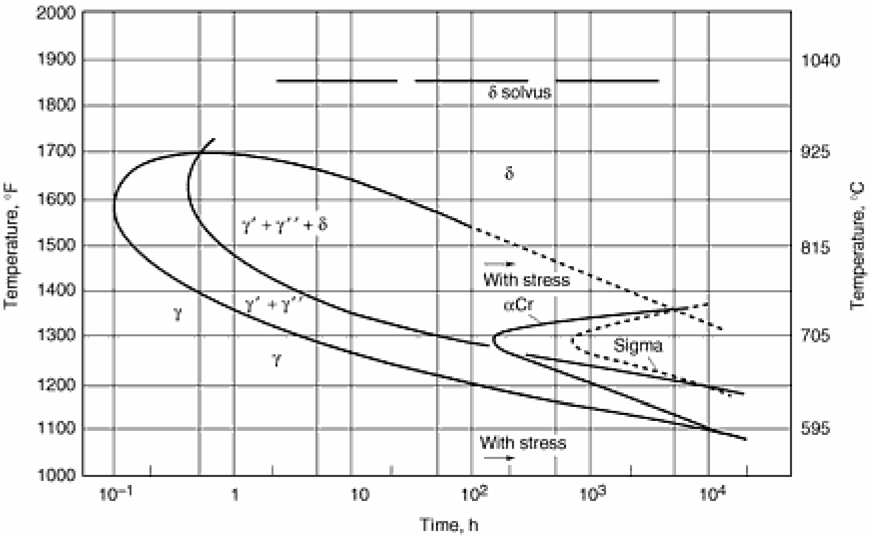

Fig. 7 TTT diagram for IN 718

Powder Processing

Powder techniques are being used extensively in superalloy production. Principally, high-strength gas turbine disk alloy compositions such as IN 100 or René 95, which are difficult or impractical to forge by conventional methods, have been powder processed. Inert atmospheres are used in the production of powders, often by gas atomization, and the powders are consolidated by extrusion or hot isostatic pressing (HIP). The latter process has been used either to produce shapes directly for final machining or to consolidate billets for subsequent forging. Extruded or HIP'ed billets often are isothermally forged to configurations for final machining. Minimal segregation, reduced inclusion sizes, ability to use very high V_f γ' compositions, and ease of grain-size control are significant advantages of the powder process. Reduced costs, particularly through HIP formation of near-net-shape disks, may be possible with powder techniques but the extent of actual cost savings is a function of alloy and part complexity. An alternative powder processing technique, the Osprey process (or variants thereof), can create a built-up article by repetitive spraying of powder onto an appropriate mandrel.

Deformation processing of powder-produced articles generally is preferred from a mechanical property standpoint. Designers tend to have more confidence in parts that have been deformation processed to some extent. The deformation processing is thought to enhance the detectability of subsurface imperfections which would limit the fracture mechanics life of the article. It is claimed that Osprey-consolidated parts may be used with or without further deformation processing, but deformation processing would be desirable. Another facet of P/M is the importance of maintaining low gas content in powder products to minimize potential defects. Sources of excessive gas in P/M superalloys include hollow argon-atomized powder particles and container leakage or insufficient evacuation and purging of containers before consolidation.

Powder techniques also have been used to produce turbine blade/vane alloys of the ODS type. Mechanical alloying is the principal technique for introducing the requisite oxide/strain energy combination to achieve maximum properties. Rapid-solidification-rate (RSR) technology has been applied to produce highly alloyed (very high V_f γ') superalloys and shows promise for advanced gas-turbine applications. Rapid-solidification-rate and ODS alloys can benefit from aligned crystal growth in the same manner as can directionally cast alloys. Directional recrystallization has been used in ODS alloys to produce favorable polycrystalline grain orientations with elongated (high-aspect-ratio) grains parallel to the major loading axis.

Investment Casting

Cobalt-base, high V_f γ' nickel-base, and IN 718 γ"-hardened superalloys are processed to complex final shapes by investment casting. Iron-nickel-base superalloys are not customarily investment cast. Investment casting permits intricate internal cooling passages and re-entrant angles to be achieved and produces a near-net shape of very precise dimensions. Most investment castings are small random-grain-oriented polycrystalline articles ranging in weight from less than a pound to a few pounds, but columnar-grain and single-crystal parts also are being cast, some as large as 4.5 to 9 kg (10 to 20 lb). In addition, large investment castings are being made in configurations up to several feet in diameter and hundreds of pounds in weight. A cast alloy commonly used to obtain the economic benefits of large sections is IN 718; a wide range of alloys are cast as smaller parts in polycrystalline, columnar-grain, or single-crystal form. Nickel-base and some cobalt-base superalloy remelting stock for investment casting is produced by VIM. Vacuum induction melted heats of superalloys intended for the investment casting process are much smaller in mass than the VIM heats used to produce stock for wrought alloy processing.

Cast articles are made by creating a pattern in wax or plastic. The pattern is duplicated as many times as necessary, typically using conventionally machined injection tooling. Hollow castings with complex internal features are produced by first creating a ceramic positive replica of the internal hollow passage through injection of a ceramic slurry into a die cavity to form a ceramic core. This core is then placed into the wax injection die and encapsulated with wax. An appropriate number of wax patterns are then attached to a "tree" complete with pourcup, sprue, risers, and so forth to channel metal from the pourcup into the part geometry.

The resulting tree is invested with ceramic of various sizes by dipping the assembled tree into a slurry, applying ceramic granules, and then drying the assembly under controlled conditions. The investing process is performed as many times as needed to build up a satisfactory ceramic coating. The invested tree is dried, and the wax is burned out. Then the investment is fired at a higher temperature to achieve maximum strength through sintering. The resulting mold is ready for use.

Many alloys are investment cast, including VIM superalloys, steels, and aluminum. These metals are melted and poured into the mold and solidified under conditions according to whether the product is to be large or small, and polycrystalline, columnar grained, or single crystal. Grain size in polycrystalline products is controlled by an appropriate primary dip coat in the investment along with mold-metal pour temperatures and selective mold insulation. An example is the Microcast-X method, which makes fine-grained (ASTM 5 to 3) superalloys by utilizing a very low superheat (low pour temperature) and a heated mold. Grain orientation in columnar-grain or single-crystal products is controlled by special furnaces that provide appropriate thermal gradients and by selective filters and/or starter nucleation sites.

After casting, the expendable ceramic shell is removed and the parts are cut from the tree. If the castings possess internal ceramic cores for internal feature fabrication, this core is removed using caustic chemicals. When removed, the positive core gives rise to the negative cavity possessing complex internal features. Most castings are typically heat treated to homogenize the metallurgical structure and precipitation strengthened to optimize mechanical properties. The castings then undergo x-ray inspection (internal defects), fluorescent penetrant inspection (external defects), chemical grain etch (crystal integrity), ultrasonic inspection (wall thickness for hollow parts), and dimensional inspection.

Inclusions, coarse grain size, surface attack in core leaching, core shift, and resulting undersized wall thickness are a few of the problems encountered in investment casting of superalloys. These problems reduce casting yield and cause potential property-level reductions if not properly controlled. Inclusions are controlled by melting technology and the use of filters to eliminate dross. Selective surface attack is controlled by modifying the autoclave leaching processes. In the past several decades, improved shell and core materials and casting mold design plus control of grain size and inclusions have led to improvements in casting yield and, occasionally, improvements in cast part strength. Casting porosity has been a problem in parts having large cross sections and in small parts made of some high V_f γ' alloys. Hot isostatic pressing techniques used for powder processing have been applied successfully in many instances to eliminate nonsurface-connected porosity, particularly in large castings of iron-nickel- and nickel-base superalloys. Improved fatigue and creep life generally result (Fig. 8), because casting quality is improved by HIP.

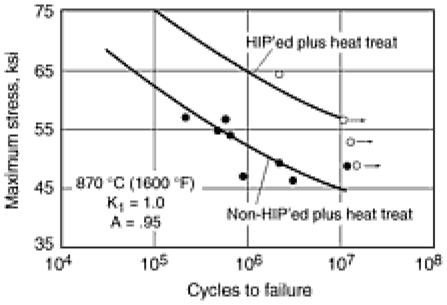

Fig. 8 Beneficial effect of HIP on high-cycle fatigue resistance of René 80

Directional-casting technology has become a commonly accepted production process for nickel-base superalloys. Columnar grain directionally solidified (CGDS) structures have been produced by promoting unidirectional heat flow within the furnace during the solidification cycle. Substantial property improvements have resulted for many alloys, Modulus parallel to the natural growth direction is lowered, leading to improvements in thermal fatigue life, ductility generally is increased, and creep-rupture strength (life) is improved through removal of transverse grain-boundary segments.

A logical extension of columnar-grain technology is the production of single crystals of hot-section aircraft gas turbine components. Removal of all grain boundaries and adjustments of alloy composition permitted by the absence of grain boundaries result in single-crystal (SC) article benefits similar to those described for the CGDS process, along with substantial improvements in strength capability. Directional casting to create a SC article provides composition flexibility and opens the possibility of additional alloy development for high-strength nickel-base superalloys. Although initially restricted to relatively small turbine airfoil components of aircraft gas turbines, CGDS, and SC processing has been extended to produce airfoils for large industrial gas turbines.

Directional solidification adds problems to those normally encountered in superalloy casting. Increased tendencies for inclusions (owing to the use of hafnium to enhance transverse ductility), separately nucleated grains, grain misorientation, and the tendency for freckle grains (grain nucleation caused by inverse segregation due to dendrite erosion) are causes for casting rejects in CGDS product. Freckles, slivers, low-angle boundaries (LAB), and spurious grains are casting problems in SC production. In both CGDS and SC alloys, surface recrystallization induced by surface strains and excess temperatures in postcast processing can be a cause for casting rejection.

Although cobalt-base superalloys can be directionally solidified in columnar grain structures, they are invariably cast as polycrystalline parts. Single-crystal manufacture of cobalt-base superalloys may be possible but has not been reported. It is doubtful that sufficiently significant property benefits would result from single-crystal or columnar-grain cobalt-base superalloys to warrant the expense of such processing.

A new technology known as rapid prototyping has enabled significant changes within the casting industry by eliminating the need for many of the investment casting process steps. This elimination has led to significant cost and lead-time reduction for development hardware. Processes such as stereolithography, selective laser sintering, and other three-dimensional printing technology can provide casting patterns without the use of costly conventional wax or ceramic injection dies. Special machines can take a three-dimensional computer-aided design (CAD), convert the design into cross-sectional layers, and build a three-dimensional representation of the CAD geometry in plastic, wax, or polymer. Some processes can directly build (from three-dimensional CAD geometry) three-dimensional ceramic shells into which metal can be poured. Other technologies focused on direct metal fabrication from three-dimensional CAD geometry are being developed. These technologies have revolutionized the industry in allowing faster development through low-cost iterative design so that design concepts can be transitioned to production rapidly.

Joining

Cobalt-base superalloys are readily joined by gas metal-arc welding (GMAW) or gas tungsten-arc welding (GTAW) techniques. Cast alloys such as WI-52 and wrought alloys such as Haynes 188 have been extensively welded. Filler metals generally have been less highly alloyed cobalt-base alloy wire, although parent rod or wire (the same composition as the alloy being welded) have been used. Cobalt-base superalloy sheet also is successfully welded by resistance techniques. Gas turbine vanes that crack in service have been repair welded using the above techniques (e.g., WI-52 vanes using L605 filler rod and 540 °C, or 1000 °F, preheat). Appropriate preheat techniques are needed in GMAW and GTAW to eliminate tendencies for hot cracking. Electron-beam welding (EBW) and plasma arc welding (PAW) can be used on cobalt-base superalloys, but usually are not required in most applications because alloys of this class are so readily weldable.

Nickel- and iron-nickel-base superalloys are considerably less weldable than cobalt-base superalloys. Because of the presence of the γ' strengthening phase, the alloys tend to be susceptible to hot cracking (weld cracking) and postweld heat treatment (PWHT) cracking (strain age or delay cracking). The susceptibility to hot cracking is directly related to the aluminum and titanium contents (γ' formers), as shown in Fig. 9. Hot cracking occurs in the weld heat-affected zone (HAZ), and the extent of cracking varies with alloy composition and weldment restraint.

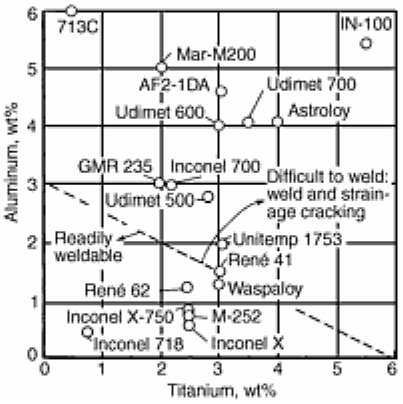

Fig. 9 Weldability diagram for some γ'-strengthened iron-nickel- and nickel-base superalloys, showing influence of total aluminum + titanium hardeners

Nickel- and iron-nickel-base superalloys have been welded by GMAW, GTAW, EBW, laser, and PAW techniques. Filler metals, when used, usually are weaker, more ductile austenitic alloys so as to minimize hot cracking. Occasionally, base-metal compositions are employed as fillers. Welding is restricted to the lower V_f γ' ($\leq$0.35) alloys, generally in the wrought condition. Cast alloys of high V_f γ'' have not been consistently welded successfully when filler metal is required, as in weld repair of service parts. However, EBW can be used to make structural joints in such alloys. Friction or inertia welding also has been successfully applied to the lower V_f γ' alloys.

Because of their γ' strengthening mechanism and capability, many nickel- and iron-nickel-base superalloys are welded in the solution-heat-treated condition. Special preweld heat treatments have been used for some alloys. Nickel-niobium alloys, as typified by IN 718, have unique welding characteristics. The hardening phase, γ'', is precipitated more sluggishly at a lower temperature than is γ' so that the attendant welding-associated strains that must be redistributed are more readily accommodated in the weld metal and HAZ. The alloy is welded in the solution-treated condition and then given a postweld stress-relief-and-aging treatment that causes γ' precipitation. Some alloys, such as A-286, are inherently difficult to weld despite only moderate levels of γ' hardeners. There is some evidence that high-titanium alloys may be more difficult to weld than alloys of similar V_f γ' relying on high aluminum/titanium ratios for their strength capabilities.

Weld techniques for superalloys must address not only hot cracking but also PWHT cracking, particularly as it concerns microfissuring (microcracking), which can be subsurface and thus difficult to detect. Tensile and stress-rupture strengths may be hardly affected by microfissuring, but fatigue strengths can be drastically reduced.

In addition to being weldable by the usual fusion welding techniques discussed above, nickel- and iron-nickel-base alloys can be resistance welded when in sheet form; brazing, diffusion bonding, and transient liquid phase (TLP) bonding also have been employed to join these alloys. Brazed joints tend to be more ductility-limited than welds; diffusion bonding of superalloys has not found consistent application. Transient liquid phase bonding has been found to be very useful, principally in turbine parts of aircraft gas turbine engines. The distinguishing characteristic of TLP bonding that produces its excellent integrity is that, although a lower-temperature bond is made as in brazing, subsequent diffusion occurs at the bonding temperature, leading to a fully solidified joint that has a composition similar to that of the base metal and a microstructure indistinguishable from it. Consequently, the resultant joint can have a melting temperature and properties very similar to those of the base metal.

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Properties and Microstructure

The principal microstructural variables of superalloys are the precipitate amount and its morphology, grain size and shape, and carbide distribution. Nickel and iron-nickel-base alloys of the titanium/aluminum type have their properties controlled by all three variables; nickel-niobium alloys have the additional variable of δ phase distribution; cobalt-base superalloys are not affected by the first variable. Structure control is achieved through composition selection/modification and by processing. For a given nominal composition, there are property advantages and disadvantages of the structures produced by deformation processing and by casting. Cast superalloys generally have coarser grain sizes, more alloy segregation, and improved creep and rupture characteristics. Wrought superalloys generally have more uniform, and usually finer, grain sizes and improved tensile and fatigue properties.

Nickel- and iron-nickel-base superalloys of the Ni-Ti/Al type typically consist of γ' dispersed in a γ matrix, and the strength increases with increasing V_f γ'. The lowest V_f amounts of γ' are found in iron-nickel-base and first-generation nickel-base superalloys, where V_f γ' is generally less than about 0.25 (25 vol%). The γ' is commonly spheroidal in lower V_f γ' alloys but often cuboidal in higher V_f γ' ($\geq$0.35) nickel-base superalloys. The nickel-niobium-type superalloys typically consist of γ'' dispersed in a γ matrix, with some γ' present as well. The inherent strength capability of the γ'- and γ''-hardened superalloys is controlled by the intragranular distribution of the hardening phases; however, the usable strength in polycrystalline alloys is determined by the condition of the grain boundaries, particularly as affected by the carbide-phase morphology and distribution, and in the case of nickel-niobium alloys, additionally by the distribution of the δ phase.

Satisfactory properties in Ni-Ti/Al alloys are achieved by optimizing the γ' V_f and morphology (not necessarily independent characteristics) in conjunction with securing a dispersion of discrete globular carbides along the grain boundaries (Fig. 10). Discontinuous (cellular) carbide or γ' at grain boundaries increases surface area and drastically reduces rupture life, even though tensile and creep strength may be relatively unaffected.

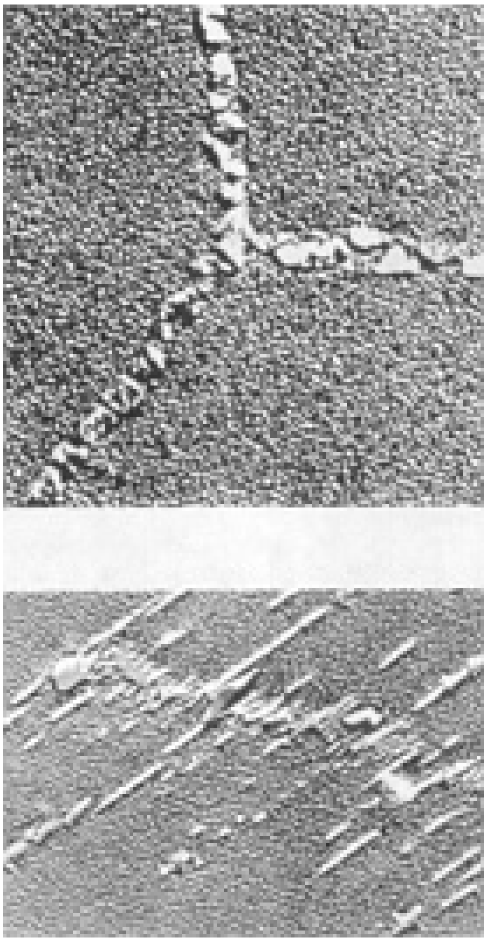

Fig. 10 Carbide precipitation in Waspaloy. (a) Favorable discrete grain-boundary type (10,000×). (b) Less favorable zipperlike, discontinuous type (6800×)

Wrought nickel- and iron-nickel-base superalloys generally are processed to have optimum tensile and fatigue properties. At one time, when wrought alloys were used for creep-limited applications, such as gas turbine high-pressure turbine blades, heat treatments different from those used for tensile-limited uses were applied to the same nominal alloy composition to maximize creep-rupture life. Occasionally, the nominal composition of an alloy such as IN 100 or U 700/Astroloy varies according to whether it is to be used in the cast or the wrought condition.

Evolution of Microstructure

Superalloys contain a variety of elements in a large number of combinations to produce desired effects. Some elements go into solid solution to provide one or more of the following: strength (molybdenum, tantalum, tungsten, rhenium); oxidation resistance (chromium, aluminum); phase stability (nickel); and increased volume fractions of favorable secondary precipitates (cobalt). Other elements are added to form hardening precipitates such as γ' (aluminum, titanium) and γ'' (niobium). Minor elements (carbon, boron) are added to form carbides and borides; these and other elements (magnesium) are added for purposes of tramp-element control. Some elements (boron, zirconium, hafnium) also are added to promote grain-boundary effects other than precipitation or carbide formation. Lanthanum has been added to some alloys to promote oxidation resistance, and yttrium has been added to coatings to enhance oxidation resistance. A major addition to nickel-base superalloy chemistry in recent years has been the element rhenium, which has extended the temperature capability of the CGDS and SC alloys. Rhenium appears to produce these improvements by significantly reducing the coarsening rate for γ'. Many elements (cobalt, molybdenum, tungsten, rhenium, chromium, etc.), although added for their favorable alloying qualities, can participate, in some circumstances, in undesirable phase formation (σ, μ, Laves, etc.).

Some of these elements produce readily discernible changes in microstructure; others produce more subtle microstructural effects. The precise microstructural effects produced are functions of processing and heat treatment. The most obvious microstructural effects involve precipitation of geometrically close-packed (gcp) phases such as γ', formation of carbides, and formation of topologically close-packed (tcp) phases such as σ. Even when the type of phase is specified, microstructure morphology can vary widely--for example, script versus blocky carbides, cuboidal versus spheroidal γ', cellular versus uniform precipitation, acicular versus blocky σ, and discrete γ' versus γ' envelopes. Typical nickel-base superalloy microstructures as they evolved from spheroidal to cuboidal γ' are depicted in Fig. 11.

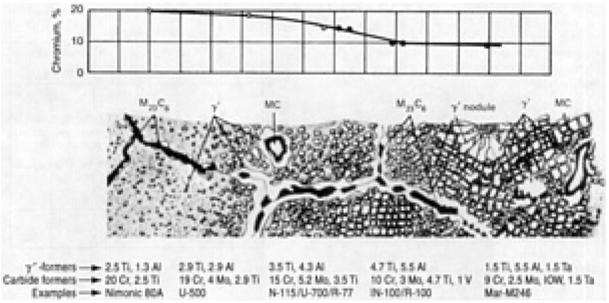

Fig. 11 Qualitative description of the evolution of microstructure and chromium content of nickel-base superalloys. Source: Adapted from Ref 3. Original source: Ref 4

The γ' phase is an ordered ($L1_2$) intermetallic fcc phase having the basic composition $Ni_3(Al,Ti)$. Alloying elements affect γ' mismatch with the matrix γphase, γ' antiphase-domain-boundary (APB) energy, γ' morphology, and γ' stability. A related phase, η, is an ordered ($D0_{24}$) hexagonal phase of composition Ni_3Ti that may exist in a metastable form as γ' before transforming to η. Other types of intermetallic phases, such as δ, orthorhombic Ni_3Nb, or γ'', bct ordered ($D0_{22}$) Ni_3Nb strengthening precipitate, have been observed.

Carbides also are an important constituent of superalloys. They are particularly essential in the grain boundaries of cast polycrystalline alloys for production of desired strength and ductility characteristics. Carbide levels in wrought alloys always have been below those in cast alloys, but some carbide has been deemed desirable for achieving optimum strength properties. As cleanliness of superalloys has increased, the carbide levels in wrought alloys have been lowered. Carbides, at least large ones, become the limiting fracture mechanics criteria for modern wrought superalloy application.

Carbides may provide some degree of matrix strengthening, particularly in cobalt-base alloys, and are necessary for grain-size control in some wrought alloys. Some carbides are virtually unaffected by heat treatment, while others require such a step to be present. Various types of carbides are possible depending on alloy composition and processing. Some of the important types are MC, M_6C, $M_{23}C_6$, and M_7C_3, where M stands for one or more types of metal atom. In many cases, the carbides exist jointly; however, they usually are formed by sequential reactions in the solid state following breakdown of the MC which normally is formed in the molten state. The common carbide-reaction sequence for many superalloys is MC to $M_{23}C_6$, and the important carbide-forming elements are chromium ($M_{23}C_6$, M_7C_3); titanium, tantalum, niobium, and hafnium (MC); and molybdenum and tungsten (M_6C). Boron may participate somewhat interchangeably with carbon and produces such phases as MB_{12}, M_3B_2, and others. One claim made for boron is that primary borides formed by adjustment of boron/carbon ratio are more amenable to morphological modification through heat treatment.

All superalloys contain some chromium plus other elements to promote resistance to environmental degradation. The role of chromium is to promote Cr_2O_3 formation on the external surface of an alloy. When sufficient aluminum is present, formation of the more protective oxide Al_2O_3 is promoted when oxidation occurs. A chromium content of 6 to 22 wt% generally is common in nickel-base superalloys, whereas a level of 20 to 30 wt% Cr is characteristic of cobalt-base superalloys, and a level of 15 to 25 wt% Cr is found in iron-nickel-base superalloys. Amounts of aluminum up to approximately 6 wt% can be present in nickel-base superalloys.

A discussion of the function of alloying elements in terms of microstructure would be incomplete without mention of the tramp elements. Elements such as silicon, phosphorus, sulfur, lead, bismuth, tellurium, selenium, and silver, often in amounts as low as the parts per million (ppm) level, have been associated with property-level reductions, but they are not visible optically or with an electron microscope. Microprobe and Auger spectroscopic analyses have determined that grain boundaries can be decorated with tramp elements at high local concentrations. Elements such as magnesium tend to tie up some detrimental elements such as sulfur in the form of a compound, and titanium tends to tie up the element nitrogen as TiN. In such cases, these and other similar compounds often are visible in the microstructure.

Function of Processing

Processing is considered to be the art/science of rendering the superalloy material into its final form. Processing and alloying elements are interdependent. The general microstructural changes brought about by processing result from the overall alloy composition plus the processing sequence. The role of heat treatment on phases will be referred to when prior microstructural effects are considered; the role of composition on phases has been discussed above. Tables 5 and 6 provide information pertaining to typical heat treatment cycles for a variety of common superalloys.

Table 5 Typical solution-treating and aging cycles for wrought superalloys

Alloy	Solution treating				Aging			
	Temperature		**Time, h**	**Cooling procedure**	**Temperature**		**Time, h**	**Cooling procedure**
	°C	**°F**			**°C**	**°F**		
Iron-base alloys								
A-286	980	1800	1	Oil quench	720	1325	16	Air cool
Discaloy	1010	1850	2	Oil quench	730	1350	20	Air cool
					650	1200	20	Air cool
N-155	1165-1190	2125-2175	1	Water quench	815	1500	4	Air cool
Incoloy 903	845	1550	1	Water quench	720	1325	8	Furnace cool
					620	1150	8	Air cool
Incoloy 907	980	1800	1	Air cool	775	1425	12	Furnace cool
					620	1150	8	Air cool
Incoloy 909	980	1800	1	Air cool	720	1325	8	Furnace cool
					620	1150	8	Air cool
Incoloy 925	1010	1850	1	Air cool	730(a)	1350(a)	8	Furnace cool

					620	1150	8	Air cool
Nickel-base alloys								
Astroloy	1175	2150	4	Air cool	845	1550	24	Air cool
	1080	1975	4	Air cool	760	1400	16	Air cool
Custom Age 625 PLUS	1038	1900	1	Air cool	720	1325	8	Furnace cool
					620	1150	8	Air cool
Inconel 901	1095	2000	2	Water quench	790	1450	2	Air cool
					720	1325	24	Air cool
Inconel 625	1150	2100	2	(b)	. . .	. . .	. . .	. . .
Inconel 706	925-1010	1700-1850	. . .	. . .	845	1550	3	Air cool
					720	1325	8	Furnace cool
					620	1150	8	Air cool
Inconel 706(c)	980	1800	1	Air cool	730	1350	8	Furnace cool
					620	1150	8	Air cool
Inconel 718	980	1800	1	Air cool	720	1325	8	Furnace cool
					620	1150	8	Air cool
Inconel 725	1040	1900	1	Air cool	730(a)	1350	8	Furnace cool
					620	1150	8	Air cool
Inconel X-750	1150	2100	2	Air cool	845	1550	24	Air cool
					705	1300	20	Air cool
Nimonic 80A	1080	1975	8	Air cool	705	1300	16	Air cool

Nimonic 90	1080	1975	8	Air cool	705	1300	16	Air cool
René 41	1065	1950	$\frac{1}{2}$	Air cool	760	1400	16	Air cool
Udimet 500	1080	1975	4	Air cool	845	1550	24	Air cool
					760	1400	16	Air cool
Udimet 700	1175	2150	4	Air cool	845	1550	24	Air cool
	1080	1975	4	Air cool	760	1400	16	Air cool
Waspaloy	1080	1975	4	Air cool	845	1550	24	Air cool
Cobalt-base alloys								
S 816	1175	2150	1	(b)	760	1400	12	Air cool

Note: Alternate treatments may be used to improve specific properties.

(a) If furnace size/load prohibits fast heat up to initial age temperature, a controlled ramp up from 590 to 730 °C (1100 to 1350 °F) is recommended.

(b) To provide adequate quenching after solution treating, it is necessary to cool below about 540 °C (1000 °F) rapidly enough to prevent precipitation in the intermediate temperature range. For sheet metal parts of most alloys, rapid air cooling will suffice. Oil or water quenching is frequently required for heavier sections that are not subject to cracking.

(c) Heat treatment of Inconel 706 to enhance tensile properties instead of creep resistance for tensile-limited applications

Table 6 Typical heat treatments for precipitation-strengthened cast superalloys

Alloy	Heat treatment (temperature/duration in h/cooling)
Polycrystalline (conventional) castings	
B-1900/B-1900 + Hf	1080 °C (1975 °F)/4/AC + 900 °C (1650 °F)/10/AC
IN-100	1080 °C (1975 °F)/4/AC + 870 °C (1600 °F)/12/AC
IN-713	As-cast

IN-718	1095 °C (2000 °F)/1/AC + 955 °C (1750 °F)/1/AC + 720 °C (1325 °F)/8/FC + 620 °C (1150 °F)/8/AC
IN-718 with HIP	1150 °C (2100 °F)/4/FC + 1190 °C (2175 °F)/4/15 ksi (HIP) + 870 °C (1600 °F)/10/AC + 955 °C (1750 °F)/1/AC + 730 °C (1350 °F)/8/FC + 655 °C (1225 °F)/8/AC
IN-738	1120 °C (2050 °F)/2/AC + 845 °C (1550 °F)/24/AC
IN-792	1120 °C (2050 °F)/4/RAC + 1080 °C (1975 °F)/4/AC + 845 °C (1550 °F)/24/AC
IN-939	1160 °C (2120 °F)/4/RAC + 1000 °C (1830 °F)/6/RAC + 900 °C (1650 °F)/24/AC + 700 °C (1290 °F)/16/AC
MAR-M246+Hf	1220 °C (2230 °F)/2/AC + 870 °C (1600 °F)/24/AC
MAR-M 247	1080 °C (1975 °F)/4/AC + 870 °C (1600 °F)/20/AC
René 41	1065 °C (1950 °F)/3/AC + 1120 °C (2050 °F)/0.5/AC + 900 °C (1650 °F)/4/AC
René 77	1163 °C (2125 °F)/4/AC + 1080 °C (1975 °F)/4/AC + 925 °C (1700 °F)/24/AC + 760 °C (1400 °F)/16/AC
René 80	1220 °C (2225 °F)/2/GFQ + 1095 °C (2000 °F)/4/GFQ + 1050 °C (1925 °F)/4/AC + 845 °C (1550 °F)/16/AC
Udimet 500	1150 °C (2100 °F)/4/AC + 1080 °C (1975 °F)/4/AC + 760 °C (1400 °F)/16/AC
Udimet 700	1175 °C (2150 °F)/4/AC + 1080 °C (1975 °F)/4/AC + 845 °C (1550 °F)/24/AC + 760 °C (1400 °F)/16/AC
Waspaloy	1080 °C (1975 °F)/4/AC + 845 °C (1550 °F)/4/AC + 760 °C (1400 °F)/16/AC
Columnar-grain (CG) castings	
DS MAR-M 247	1230 °C (2250 °F)/2/GFQ + 980 °C (1800 °F)/5/AC + 870 °C (1600 °F)/20/AC
DS MAR-M200+Hf	1230 °C (2250 °F)/4/GFQ + 1080 °C (1975 °F)/4/AC + 870 °C (1600 °F)/32/AC
DS René 80H	1190 °C (2175)/2/GFQ + 1080 °C (1975 °F)/4/AC + 870 °C (1600 °F)/16/AC
Single-crystal castings	
CMSX-2	1315 °C (2400 °F)/3/GFQ + 980 °C (1800 °F)/5/AC + 870 °C (1600 °F)/20/AC
PWA 1480	1290 °C (2350 °F)/4/GFQ + 1080 °C (1975 °F)/4/AC + 870 °C (1600 °F)/32/AC

René N4	1270 °C (2320 °F)/2/GFQ + 1080 °C (1975 °F)/4/AC + 900 °C (1650 °F)/16/AC

AC, air cooling; FC, furnace cooling; GFQ, gas furnace quench; RAC, rapid air cooling

The three most significant process-related microstructural variables other than those resulting from composition/heat treatment interactions are the size, shape, and orientation (in anisotropic structures) of the grains. Grain size varies considerably from cast to wrought structure, generally being significantly smaller for the latter. Special processing--for example, directional solidification or directional recrystallization--can effect changes not only in grain size but also in grain shape and orientation, which significantly alter mechanical and physical properties. Corrosion reactions, however, are primarily functions of composition.

Effects of Prior Microstructure on Properties

Nickel- and iron-nickel-base superalloys may be hardened by γ' or γ'' precipitation (in an fcc γ matrix). The γ' in iron-nickel-base and first-generation nickel-base alloys generally is spheroidal, whereas the γ' in later-generation nickel-base alloys generally is cuboidal (Fig. 12). The γ'' phase is disk shaped. The V_f of γ' is generally approximately 0.2 or less in wrought iron-nickel-base superalloys but may exceed 0.6 in nickel-base superalloys. There are insufficient alloy compositions to provide knowledge of a range for V_f γ'' in γ''-hardened alloys.

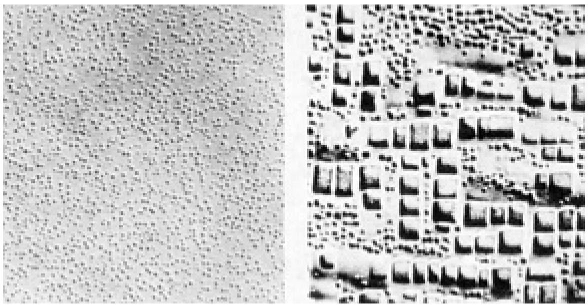

Fig. 12 Wrought nickel-base superalloys showing spheroidal nature of early (low V_f γ') alloys (Waspaloy, left) and cuboidal nature of later (higher V_f γ') alloys (U 700, right). Note secondary (cooling) γ' between primary cuboidal γ' particles in U 700. Original magnification, 6800×

γ' Precipitation. Strengthening by precipitate particles is related to many factors; in the case of γ', the most direct correlations can be made with V_f of γ' and with γ' particle size. However, the correlation between strength and γ' size may be difficult to prove in commercial alloys over the range of particle sizes available. Before the age-hardening peak is reached during precipitation, the operative strengthening mechanism involves cutting of γ' particles by dislocations, and strength increases with increasing γ' size (Fig. 13) at constant V_f of γ'. After the age-hardening peak is reached, strength decreases with continuing particle growth because dislocations no longer cut γ' particles but rather bypass them. This effect can be demonstrated for tensile or hardness behavior in low V_f γ' alloys (A-286, Incoloy 901, Waspaloy), but is not as readily apparent in high V_f γ' alloys such as MAR-M 246, IN 100, and so forth. For creep rupture, the effects are less well defined; however, uniform fine-to-moderate γ' sizes (0.25 to 0.5 μm) are preferred to coarse or hyperfine γ' for optimum properties.

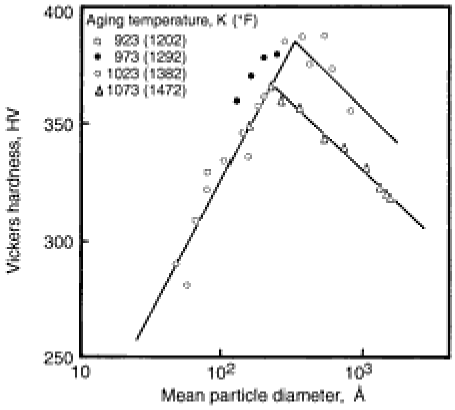

Fig. 13 Strength (hardness) versus particle diameter in a nickel-base superalloy. Cutting occurs at low particle sizes, bypassing at larger sizes. Note that aging temperature also affects strength in conjunction with particle size.

Alloy strength in titanium/aluminum hardened alloys clearly depends on V_{f} γ'. The V_{f} γ' and thus strength can be increased to a point by adding more hardener elements (aluminum, titanium). Alloy strengths increase as aluminum + titanium content increases (Fig. 14), and also as the aluminum-to-titanium ratio increases. In wrought alloys, the γ' usually exists as a bimodal (duplex) distribution of fine γ', and all of the aluminum + titanium contributes effectively to the hardening process. In cast alloys, the character of the γ' precipitate developed can be extremely variable because of the effects of segregation and cooling rate. Large amounts of γ-γ' eutectic and coarse γ' may be developed during solidification. Subsequent heat treatment can modify these structures. Bimodal and trimodal γ' distributions plus γ-γ' eutectic can be found in cast alloys after heat treatment. Solution heat treatments at temperatures sufficiently high to homogenize the alloy and dissolve coarse γ' and the eutectic γ-γ' constituents for subsequent reprecipitation as a uniform fine γ' have improved creep capability. However, incipient melting temperatures limit the homogenization possible in many polycrystalline or CGDS super-alloys. For a columnar-grain nickel-base superalloy, a direct correlation has been found to exist between creep-rupture life at 980 °C (1800 °F) and the V_{f} of fine γ' (Fig. 15).

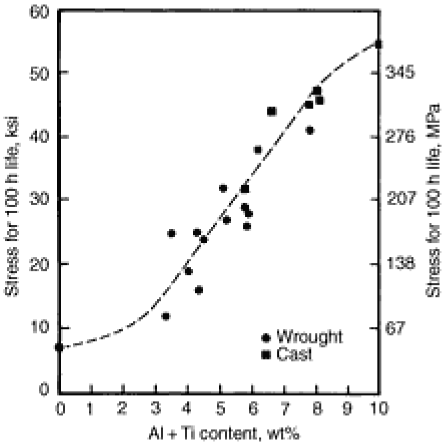

Fig. 14 Effect of aluminum + titanium content on strength of wrought and cast nickel-base superalloys at 870 °C (1600 °F)

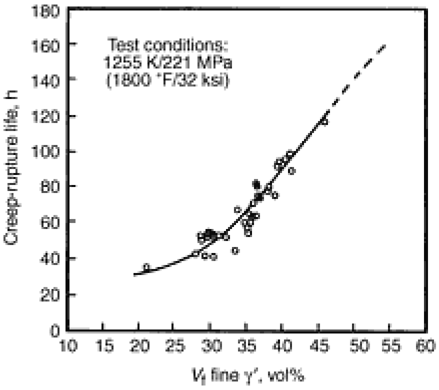

Fig. 15 Increase in creep-rupture life with increase in V_f of fine γ', demonstrated in a columnar-grain, directionally solidified nickel-base superalloy, PWA 1422 (variant of MarM-200, with hafnium addition)

In general, to achieve the greatest hardening in γ'-hardened alloys it is necessary to solution heat treat the alloys above the γ' solvus. One or more aging treatments are used to optimize the γ' distribution and to promote transitions in other phases such as carbides. In some alloys, several intermediate and several lower-temperature aging treatments are used; in cast alloys or in very high V_f γ' wrought alloys, a coating cycle or high-temperature aging treatment may precede the intermediate-temperature aging cycle. When multiple aging treatments are used, a superalloy may show the bimodal or trimodal γ' distribution described above. An essential feature of γ' hardening in nickel-base superalloys is that a temperature fluctuation that dissolves some γ' does not necessarily produce permanent property damage, because subsequent cooling to normal operating conditions reprecipitates γ' in a useful form.

In the final analysis, it is not possible to judge alloy performance by considering just the γ' phase. The strength of γ'-hardened grains must be balanced by grain-boundary strength. If the γ'-hardened matrix becomes much stronger relative to grain boundaries, then premature failure occurs because stress relaxation at the grain boundaries becomes difficult.

γ'' Precipitation. The γ'' phase relationship to properties has not been studied extensively. Strength will be a function of V_f of γ''; however, any quantitative relationships established for γ'-hardened alloys will not hold for γ''-hardened alloys because of a difference in precipitate morphology (the γ'-hardened alloys use initial precipitates which are cuboids or spheres, while the γ'' precipitates are disks). The nickel-niobium alloys tend to have reversion or dissolution of the strengthening phase at relatively low temperatures. Bimodal γ'' distributions are not necessarily found, but γ'' coupled with γ' distributions form.

Heat treatments for the nickel-niobium alloys attempt to optimize the distribution of the γ'' phase as well as to control grain size. Although for many years, a sequence of solution treatment followed by two-step aging was the preferred route to an appropriate γ'' distribution after an article was forged, this is no longer the case. This sequence has been replaced in most instances by a direct-age process after cooling of the nickel-niobium alloy article from the forging temperature. Uniform γ'' distributions with attendant γ' precipitate are formed. See the following discussion and the prior discussion of direct aging in IN 718 in the "Deformation Processing" section.

The practical use of γ'' precipitation is restricted to nickel-base alloys with niobium additions in excess of 4 wt%. IN 718 is the outstanding example of an alloy in which γ'' formation has been commercially exploited. The V_f of γ'' in IN 718 is substantially in excess of that of γ'. Both γ'' and γ' will be found in alloys where γ'' is present, but γ'' will be the predominant strengthening agent. Although the strengthening behavior of γ'' phase has not been studied, similar considerations to γ' behavior as described earlier probably pertain; that is, there will be an optimum γ'' size and V_f for strength. The most significant feature of γ'' is probably the ease with which it forms at moderate temperatures after prior solutioning by heat treatment or joining processes. Because of this behavior, a γ''-hardened alloy can be aged, after welding, to produce a fully strengthened structure with exceptional ductility.

The γ'' phase, not normally a stable phase, can convert to γ' and δNi_3Nb on longtime exposure. The strength of γ' is additive to that of γ'' phase. A lack of notch ductility in IN 718 has been associated with a γ'' precipitate-free zone (PFZ); the γ'' PFZ can be eliminated and ductility restored by appropriate heat treatment. Alloys hardened with γ'' phase achieve high tensile strengths and very good creep-rupture properties at lower temperatures, but the conversion of γ'' to γ and δ above approximately 675 °C (1250 °F) causes a sharp reduction in strength.

Carbide Precipitation: Grain-Boundary Hardening. Carbides exert a profound influence on properties by their precipitation on grain boundaries. In most superalloys, $M_{23}C_6$ forms at the grain boundaries after a postcasting or postsolution treatment thermal cycle such as aging. Chains of discrete globular $M_{23}C_6$ carbides were found to optimize creep-rupture life by preventing grain-boundary sliding in creep rupture while concurrently providing sufficient ductility in the surrounding grain for stress relaxation to occur without premature failure.

In contrast, if carbides precipitate as a continuous grain-boundary film, properties can be severely degraded. $M_{23}C_6$ films were reported to reduce impact resistance of M252, and MC films were blamed for lowered rupture lives and ductility in forged Waspaloy. At the other extreme, when no grain-boundary carbide precipitate is present, premature failure will also occur because grain-boundary movement essentially is unrestricted, leading to subsequent cracking at grain-boundary triple points.

The role of carbides at grain boundaries in iron-nickel-base superalloys is less well documented than for nickel-base alloys, although detrimental effects of carbide films have been reported. Studies of specific effects of grain-boundary carbides in cobalt-base alloys are even more sparse, because the carbide distribution in cobalt-base alloys arises from the original casting or on cooling after mill annealing for wrought cobalt-base alloys. The significantly greater carbon content of cobalt-base alloys leads to much more extensive grain-boundary carbide precipitation than in nickel- and iron-nickel-base alloys. Carbides at grain boundaries in cast cobalt-base alloys appear as eutectic aggregates of M_6C, $M_{23}C_6$, and fcc γ cobalt-base solid solution. No definitive study of the effects of varied carbide forms in grain boundaries on the mechanical behavior of cobalt-base superalloys has been reported.

The lamellar eutectic (carbides-γ Co) nature of carbides ($M_{23}C_6$-M_6C) in cast cobalt-base superalloys is interesting. A somewhat similar morphology of $M_{23}C_6$, occurring when it is precipitated in cellular form in nickel- and iron-nickel-base alloys, leads to mechanical-property loss in such alloys, but lamellar eutectic does not seem to degrade cast cobalt-base alloy properties. Cellular growth in nickel-base alloys was found to occur when a high supersaturation of carbon produced by solution heat treatment was not relieved by an intermediate precipitation treatment prior to aging at 705 to 760 °C (1300 to 1400 °F). The ductility of a nickel-base superalloy also was impaired by a different type of precipitation--namely, Widmanstätten M_6C at grain and twin boundaries. However, formation of intragranular Widmanstätten M_6C after exposure of B-1900 nickel-base alloy did not appear to reduce properties.

Another effect produced by grain-boundary $M_{23}C_6$ carbide precipitation is the occasional formation, on either side of the boundary, of a zone depleted in γ' precipitate. These PFZs may have significant effects on rupture life of nickel- and iron-nickel-base superalloys. If such zones should become wide or much weaker than the matrix, deformation would concentrate there, resulting in early failure. The more complex (higher V_f γ') alloys do not show significant PFZ effects, probably because of their higher saturation with regard to γ'-forming elements. An effect seen concurrently with PFZ and not clearly separated from it is the γ' envelope produced by breakdown of TiC and consequent formation of $M_{23}C_6$ or M_6C + γ' (from the excess titanium). Not only is the role of the γ' envelope insufficiently established, but there is also the remote possibility that the excess titanium-rich area is really either η or a metastable γ' that could transform to η in use.

Carbide Precipitation: Matrix or General Hardening. Carbides affect the creep-rupture strengths of cobalt-base superalloys and some nickel- and iron-nickel base superalloys by formation within grains. In cobalt-base cast superalloys, script MC carbides are liberally interspersed within grains, causing a form of dispersion hardening that is not of a large magnitude owing to its relative coarseness. The distribution of carbides in cast alloys can be modified by heat treatment, but strength levels attained at all but the highest temperatures are substantially less than those of the γ'-hardened alloys. Consequently, cast cobalt-base alloys generally are not heat treated except in a secondary sense through the coating diffusion heat treatment of 4 h at 1065 to 1120 °C (1950 to 2050 °F) sometimes applied.

Wrought cobalt-base superalloys have carbide modifications produced during the fabrication sequence. Carbide distributions in wrought alloys result from the mill anneal after final working. Properties are largely a result of grain size, refractory-metal content, and carbon level, which indicates the V_f of carbides available for hardening.

True solutioning, in which all minor constituents are dissolved, is not possible in most cobalt-base superalloys, because melting often occurs before all the carbides are solutioned. Some enhancement of creep rupture behavior has been achieved by heat treatment. Rupture-time improvements can be gained by aging a modified Vitallium alloy (Fig. 16); larger increases have been produced by increasing the carbon content of the alloy. Solution treating and aging is not suitable for producing stable cobalt-base superalloys for use above 815 °C (1500 °F) because of carbide dissolution or overaging.

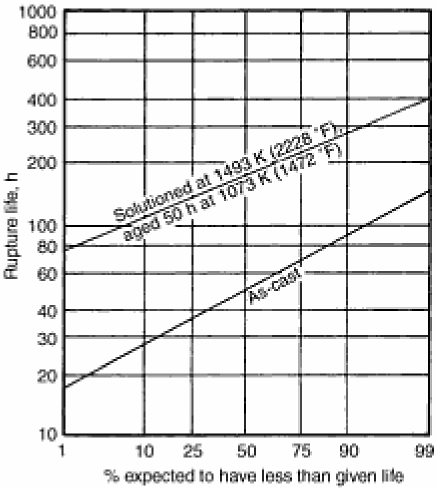

Fig. 16 Effect of heat treatment on a cobalt-base superalloy (HS-31, also known as X-40), showing increase in strength resulting from carbide precipitation

Matrix carbides in nickel- and iron-nickel-base superalloys also may be partially solutioned. MC carbides will not totally dissolve, however, without incipient melting of the alloy and tend to be unstable, decomposing to $M_{23}C_6$ at temperatures below about 815 to 870 °C (1500 to 1600 °F) or possibly converting to M_6C at temperatures of 980 to 1040 °C (1800 to 1900 °F) if the alloy has a sufficiently high molybdenum + tungsten content. Matrix carbides generally contribute very small increments of strengthening to nickel- and iron-nickel-base superalloys.

An interesting microstructural trend has taken place with the advent of single crystals of nickel-base superalloys. Because no grain boundaries exist, there is little need for the normal grain-boundary strengtheners such as carbon. Consequently, very few matrix or subboundary carbides exist in first-generation SC alloys. Although the initial trend was to remove carbon completely from SC nickel-base superalloys, the subsequent realization that subboundaries in single crystals could benefit from carbides has led to a relaxation of carbon restrictions, and low amounts of carbon are now permitted in many single-crystal alloys. (Hafnium, boron, and zirconium in limited amounts also may be permitted.) As noted above, the trend in wrought nickel-base superalloys continues to be toward reduced carbon and reduced carbide size.

Perhaps the most common other role of matrix carbides (also shared by grain-boundary carbides) is a negative one: They may participate in the fatigue cracking process by premature cracking or by oxidizing at the surface of uncoated alloys to cause a notch effect. Oxidized carbides or precracked carbides from machining or thermal stresses can initiate fatigue cracks. Precracked carbides can be related to prior casting processes. Carbide size is important, and reduced carbide volumes and sizes in nickel-base alloys result in a reduction in precracked carbides. The longer solidification times and lower gradients of early directional solidification processes often resulted in moderately large carbides. However, improved gradients and the reduced carbon contents of SC alloys (few or no carbides) have resulted in substantial improvements in fatigue resistance, particularly over similarly oriented CGDS alloys with normal carbon levels. This effect is most noticeable in low-cycle fatigue (LCF) and thermomechanical fatigue (TMF). No evidence is available to interpret the effect of the absence of carbides on high-cycle fatigue (HCF), but beneficial effects could be anticipated.

Oxidized carbides can be minimized or prevented by several methods. Casting procedures and/or chemical composition may be modified to produce smaller primary carbides. Powder processing may be used to produce the same result. Carbon content may be reduced if it is not specifically required to enable the alloy to attain the desired strength levels. Reduced carbon is the rule in SC and powdered superalloys. Of course, the alloy may be coated with an appropriate protective coating that leaves the carbides in a subsurface location.

Although there is limited documentation, it frequently is assumed that noncarbide-forming elements do influence the formation of carbides. Cobalt, for example, has been claimed to modify the carbides in nickel-base alloys, and phosphorus has produced a more general, more finely dispersed, and smaller carbide precipitation than carbon alone in a heat-resisting iron-base alloy. The modifying effect on carbides may be intragranular or intergranular depending on the modifier and the base-alloy system.

Boron, Zirconium, and Hafnium. Within limits, significant improvements in mechanical properties can be achieved by additions of boron, zirconium, and hafnium. However, only limited microstructural correlations can be made. The presence of these elements may modify the initial grain-boundary carbides or tie up deleterious elements such as sulfur and lead. Reduced grain-boundary diffusion rates may be obtained, with consequent suppression of carbide agglomeration and creep cracking. Hafnium contributes to the formation of more γ-γ' eutectic in cast alloys; the eutectic at grain boundaries is thought (in modest quantities) to contribute to alloy ductility. The effects of these elements are limited to nickel- and iron-nickel-base alloys; virtually no cobalt-base alloys contain them. Hafnium in particular contributes strongly to improved ductility in transverse boundaries in CGDS alloys.

Processing. Three major processing techniques are used for controlling superalloy properties. Thermomechanical working is used for wrought nickel- and iron-nickel-base alloys to store energy by producing a fine grain size and controlling dislocation density/configuration. Improvements in tensile properties and LCF have resulted.

A second processing route involves the use of powder metallurgy to produce reduced carbide size and greater homogeneity in materials with a resultant improvement in fatigue resistance and fracture mechanics life limits. Furthermore, in conjunction with isothermal processing, alloy grain sizes of ASTM 8 to 12 are being routinely produced in very-high-strength alloys, resulting in additional fatigue-life benefits. (Major benefits result from the ability to form alloys such as IN 100, which are unforgeable by some standard procedures.)

The third area is casting control of grain size and morphology, especially by controlled solidification. Cast-alloy grain sizes have been made more uniform and, in some cases, have been reduced to enhance fatigue or tensile properties. Directional grain structures have improved strength (Fig. 17). Improved creep-rupture and fatigue resistance have resulted from the elimination of transverse grain boundaries and the favorable orientation of a low modulus direction to reduce strains. In the extreme, grains have been eliminated in SC alloys with additional gains in creep-rupture behavior (Fig. 17).

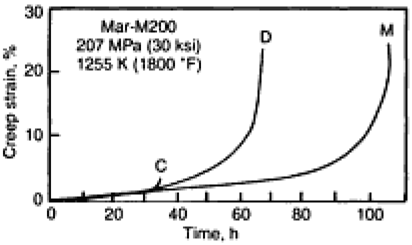

Fig. 17 Comparison of creep properties of MAR-M 200 alloy, polycrystalline conventionally cast (C), columnar-grain directionally solidified (D), and single-crystal directionally solidified (M)

Porosity in superalloys has led to fatigue and creep-rupture failure. Reduced porosity owing to HIP has resulted in improved properties. Efforts to date have centered on nickel-base cast alloys, but the process should enhance properties of any cast alloy with nonsurface-connected casting porosity. (In the biomedical field, use of HIP has provided significant improvements in fatigue life of cast Vitallium alloy hip replacements.)

Effects of Thermal Exposure on Mechanical Properties

Superalloys generally behave much like other alloy systems on thermal exposure during testing or in service, but with some differences due to the nature of the γ' precipitates. Most alloys with secondary hardening phases undergo property degradation due to coalescence of the secondary phases, a process that reduces their effectiveness. This behavior occurs in superalloys and is manifested by such phenomena as γ' agglomeration and coarsening; carbide precipitation and γ' envelope formation also occur. In addition, the superalloys may show a tendency to form less-desirable secondary phases such as σ.

These detrimental phases generally reduce property levels of the superalloys in which they form because of their inherent properties and/or the consumption of elements intended for γ and γ'. Some of these phases can be prevented from forming by application of compositional control guided by the concept of the electron-vacancy number, N_v. Formation of tcp phases such as σ, Laves, and μ is found to be related to excess electron vacancies in the transition-element base metals (iron, nickel, and cobalt). By ascribing N_v values to the alloying elements of the γ matrix, a weighted N_v can be calculated for γ, and, by experiment, upper limits for N_v can be set for a given alloy composition to ensure the absence of tcp phases in reasonable exposure times. Unfortunately, simple calculations of this type have not been found applicable to δ or η formation, which can be detrimental in certain morphologies and/or in excess amounts. Trial-and-error adjustments of composition and processing generally are required to ensure that δ and η precipitation do not occur and cause a significant loss of properties.

In addition to the formation of a singular detrimental phase, a more complex microstructure can appear under coatings. A specific secondary reaction zone (SRZ) was reported for alloys of the N4 and N5 type. This zone produced a transformation front which often occurred as a cellular reaction in which γ and P phase (about 50% Re) formed in a matrix of γ' phase. Strength was dramatically reduced, especially when SRZ formed in dendritic areas. Modified alloys have negated the formation of this complex structure, just as N_v control minimizes formation of detrimental tcp phases.

Transformation of Hardening Phase. In iron-nickel-base superalloys, the strengthening precipitate usually degrades in a moderate temperature regime, 650 to 760 °C (1200 to 1400 °F), forming structures and precipitate morphologies that are less effective in strengthening the alloy. In alloys hardened by large amounts of titanium, η phase replaces γ'. The precipitation of η may occur in two forms: at the grain boundaries as cellular product or intragranularly as Widmanstätten plates. The cellular precipitation is often associated with loss of mechanical properties, particularly notch stress rupture (NSR). Intragranular plates also may cause some property loss, but data are not available. In some nickel-base superalloys with higher titanium/aluminum ratios (e.g., IN 738, IN 792, and IN 939), η has been reported, but no information on property degradation is available.

In a nickel-niobium alloy such as IN 718, plates of orthorhombic δ phase will form on exposure after sufficiently long times at elevated temperatures. Because of its relatively coarse morphology, properties deteriorate when excess amounts of platelike or acicular δ form.

Formation of Transition-Element Phases. Of great concern in all superalloys has been the formation of detrimental secondary phases not directly associated with the primary hardening precipitate phases, γ' and γ''. Laves phases have been found in the iron-nickel-base superalloys IN 718, Incoloy 901, and A-286. Room-temperature yield strength and ductility of IN 718 are reduced by Laves formation, whereas Laves in A-286 does not affect properties. Laves in the cobalt-base alloy L605 severely degrades room-temperature ductility.

Phases such as Laves, σ, and μ in acicular form generally are detrimental owing to their morphology, lack of ductility, and the tying up of some hardening elements. Sigma-phase formation in several nickel-base alloys has been shown to reduce stress-rupture life (Fig. 18). Sigma generally forms with exposure and is controlled by establishing composition limits (phase control electron vacancy number, N_v) or by preventing an alloy from operating in the σ-forming temperature range. The extent of the effect that tcp and other secondary phases have on properties varies with the type of alloy (cast versus wrought), property being measured, initial microstructure, and environmental effects (coated versus uncoated, test atmosphere).

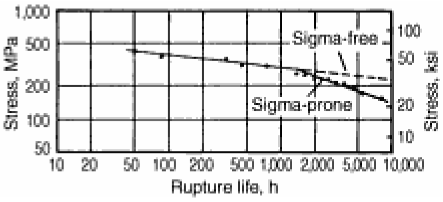

Fig. 18 Stress-rupture behavior of U 700, showing reduction in strength that occurs when σ phase forms. Source: Ref 5 (original source: Ref 6)

Morphological Changes in γ'. Changes in γ' during testing produce effects on properties that may not be readily observed because of the simultaneous occurrence of other microstructural changes. Most commonly, γ' coarsens following well-established kinetics and agglomerates in a creep-rupture test (Fig. 19), tending to form platelets of γ' on the [001] planes perpendicular to the applied stress. The coarsening of γ' can cause reduced rupture life (Fig. 20). Overheating can cause accelerated coarsening as well as solutioning of some fine γ'. Properties may be reduced, but reprecipitation of fine γ' occurs in the case of mild overheating excursions.

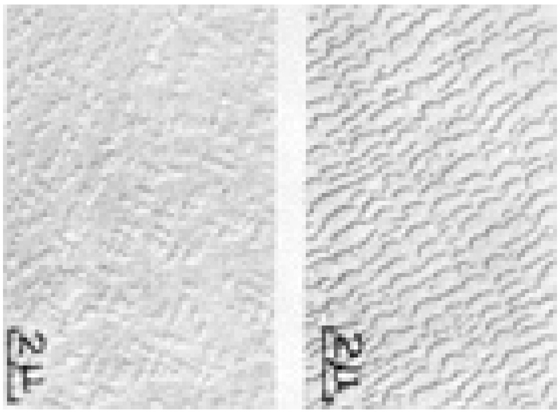

Fig. 19 Agglomeration of γ' in Udimet 700 resulting from creep testing. Left, as heat treated. Right, after 91.2 h at 252.3 MPa (36.6 ksi) and 893 °C (1640 °F). 4000×

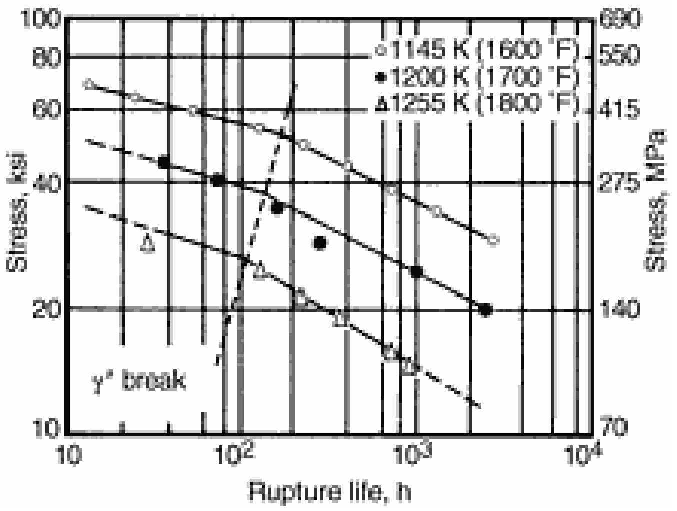

Fig. 20 Stress-rupture behavior of B-1900 nickel-base superalloy, showing break in slope believed to be caused

by γ' coarsening

Carbide Morphology/Type Changes. As exposure time increases, there is a tendency for further reduction in the primary MC carbide amounts and for further morphological changes together with a tendency to form increased amounts of the secondary carbides $M_{23}C_6$ and M_6C. If carbide films form and/or acicular carbides of the M_6C type form, alloy ductility and strength can be reduced. Agglomeration of carbides, however, can lead to increased ductility accompanied by strength reduction.

In cast cobalt-base superalloys, precipitation of additional intragranular carbides during service has led to sharply increased rupture strength and reduced rupture ductility. The precipitation of an intragranular acicular Widmanstätten carbide brought about by aging in another cobalt-base alloy degraded both rupture life and ductility.

Property Recovery after Thermal Exposure. As noted, changes in γ' occur with exposure to elevated temperatures. Most commonly, γ' coarsens and agglomerates, particularly under stress. Overheating can cause accelerated coarsening as well as solutioning of some fine γ'. Properties may be reduced in such circumstances, but when the overheating has been mild, reprecipitation of fine γ' occurs with a return to normal temperatures, and some property recovery occurs. Property recovery, however, does not occur in the case of additional thermal exposure of tcp, δ, or η phases in superalloys. Nor is recovery achieved by thermal exposure after excessive carbide precipitation (as may occur in cobalt-base superalloys) or after extensive γ' coarsening (as in nickel- and iron-nickel-base superalloys).

Recovery of properties is desired as a means of prolonging component life. If, as above, additional thermal exposure fails to promote better properties, then re-solution heat treatment and aging is required to restore property levels. While this process may be satisfactory in alloys degraded only by thermal exposure, service exposure under stress generally produces property losses (due in part to cavitation or wedge creep cracking), which cannot be recovered by simple heat treatment alone--at least for the more complex commercial superalloys. The use of HIP plus re-solution and aging treatment of exposed superalloys has suggested that some improvements can be achieved under suitable circumstances, but the extent to which such salvage processing is economically viable is uncertain.

Typical Mechanical Properties of Superalloys

In this discussion, "typical" means the most likely value to be reached for a given property in a standard test if one were to conduct random testing. Typical properties are merely a guide for comparison. Exact chemistry, section size, heat treatment, and other processing steps must be known to generate property for design. Tables 7 and 8 summarize property behavior for wrought alloys; Tables 9 and 10 provide similar information for cast alloys.

Table 7 Effect of temperature on the mechanical properties of wrought nickel-, iron-, and cobalt-base superalloys

Alloy	Form	Ultimate tensile strength at:						Yield strength at 0.2% offset at:						Tensile elongation, % at:		
		21 °C (70 °F)		**540 °C (1000 °F)**		**760 °C (1400 °F)**		**21 °C (70 °F)**		**540 °C (1000 °F)**		**760 °C (1400 °F)**		**21 °C (70 °F)**	**540 °C (1000 °F)**	**760 °C (1400 °F)**
		MPa	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**			
Nickel-base																
Astroloy	Bar	1415	205	1240	180	1160	168	1050	152	965	140	910	132	16	16	21
Cabot 214	. . .	915	133	715	104	560	84	560	81	510	74	495	72	38	19	9

D-979	Bar	1410	204	1295	188	720	104	1005	146	925	134	655	95	15	15	17
Hastelloy C-22	Sheet	800	116	625	91	525	76	405	59	275	40	240	35	57	61	63
Hastelloy G-30	Sheet	690	100	490	71	. . .	. . .	315	46	170	25	. . .	. . .	64	75	. . .
Hastelloy S	Bar	845	130	775	112	575	84	455	65	340	49	310	45	49	50	70
Hastelloy X	Sheet	785	114	650	94	435	63	360	52	290	42	260	38	43	45	37
Haynes 230	(a)(b)	870	126	720	105	575	84	390	57	275	40	285	41	48	56	46
Inconel 587(c)	Bar	1180	171	1035	150	830	120	705	102	620	90	605	88	28	22	20
Inconel 597(c)	Bar	1220	177	1140	165	930	135	760	110	720	104	665	96	15	15	16
Inconel 600	Bar	660	96	560	81	260	38	285	41	220	32	180	26	45	41	70
Inconel 601	Sheet	740	107	725	105	290	42	455	66	350	51	220	32	40	34	78
Inconel 617	Bar	740	107	580	84	440	64	295	43	200	29	180	26	70	68	84
Inconel 617	Sheet	770	112	590	86	470	68	345	50	230	33	230	33	55	62	59
Inconel 625	Bar	965	140	910	132	550	80	490	71	415	60	415	60	50	50	45
Inconel 706	Bar	1310	190	1145	166	725	105	1005	146	910	132	660	96	20	19	32
Inconel 718	Bar	1435	208	1275	185	950	138	1185	172	1065	154	740	107	21	18	25
Inconel 718 Direct Age	Bar	1530	222	1350	196	. . .	. . .	1365	198	1180	171	. . .	. . .	16	15	. . .

Inconel 718 Super	Bar	1350	196	1200	174	. . .	. . .	1105	160	1020	148	. . .	. . .	16	18	. . .
Inconel X750	Bar	1200	174	1050	152	. . .	. . .	815	118	725	105	. . .	. . .	27	26	. . .
M-252	Bar	1240	180	1230	178	945	137	840	122	765	111	720	104	16	15	10
Nimonic 75	Bar	745	108	675	98	310	45	285	41	200	29	160	23	40	40	67
Nimonic 80A	Bar	1000	145	875	127	600	87	620	90	530	77	505	73	39	37	17
Nimonic 90	Bar	1235	179	1075	156	655	95	810	117	725	105	540	78	33	28	12
Nimonic 105	Bar	1180	171	1130	164	930	135	830	120	775	112	740	107	16	22	25
Nimonic 115	Bar	1240	180	1090	158	1085	157	865	125	795	115	800	116	27	18	24
Nimonic 263	Sheet	970	141	800	116	650	94	580	84	485	70	460	67	39	42	21
Nimonic 942(c)	Bar	1405	204	1300	189	900	131	1060	154	970	141	860	125	37	26	42
Nimonic PE.11(c)	Bar	1080	157	1000	145	760	110	720	105	690	100	560	81	30	30	18
Nimonic PE.16	Bar	885	128	740	107	510	74	530	77	485	70	370	54	37	26	42
Nimonic PK.33	Sheet	1180	171	1000	145	885	128	780	113	725	105	670	97	30	30	18
Pyromet 860(c)	Bar	1295	188	1255	182	910	132	835	121	840	122	835	121	22	15	18
René 41	Bar	1420	206	1400	203	1105	160	1060	154	1020	147	940	136	14	14	11
René 95	Bar	1620	235	1550	224	1170	170	1310	190	1255	182	1100	160	15	12	15
Udimet	Bar	1310	190	1185	172	. . .	. . .	930	135	830	120	. . .	. . .	30	26	. . .

400(c)																
Udimet 500	Bar	1310	190	1240	180	1040	151	840	122	795	115	730	106	32	28	39
Udimet 520	Bar	1310	190	1240	180	725	105	860	125	825	120	725	105	21	20	15
Udimet 630(c)	Bar	1520	220	1380	200	965	140	1310	190	1170	170	860	125	15	15	5
Udimet 700	Bar	1410	204	1275	185	1035	150	965	140	895	130	825	120	17	16	20
Udimet 710	Bar	1185	172	1150	167	1020	148	910	132	850	123	815	118	7	10	25
Udimet 720	Bar	1570	228	. . .	. . .	1455	211	1195	173	. . .	. . .	1050	152	13	. . .	9
Unitemp AF2-1DA6	Bar	1560	226	1480	215	1290	187	1015	147	1040	151	995	144	20	19	16
Waspaloy	Bar	1275	185	1170	170	650	94	795	115	725	105	675	98	25	23	28
Iron-base																
A-286	Bar	1005	146	905	131	440	64	725	105	605	88	430	62	25	19	19
Alloy 901	Bar	1205	175	1030	149	725	105	895	130	780	113	635	92	14	14	19
Discaloy	Bar	1000	145	865	125	485	70	730	106	650	94	430	62	19	16	. . .
Haynes 556	Sheet	815	118	645	93	470	69	410	60	240	35	220	32	48	54	49
Incoloy 800(c)	Bar	595	86	510	74	235	34	250	36	180	26	150	22	44	38	83
Incoloy 801(c)	Bar	785	114	660	96	325	47	385	56	310	45	290	42	30	28	55
Incoloy 802(c)	Bar	690	100	600	87	400	58	290	42	195	28	200	29	44	39	15

Incoloy 807(c)	Bar	655	95	470	68	350	51	380	55	255	37	225	32.5	48	40	34
Incoloy 825(d)(e)	. . .	690	100	∼590	∼86	∼275	∼40	310	45	∼234	∼34	180	∼26	45	∼44	∼86
Incoloy 903	Bar	1310	190	. . .	. . .	. . .	. . .	1105	160	. . .	. . .	. . .	. . .	14	. . .	. . .
Incoloy 907(d)(f)	. . .	∼1365	∼198	∼1205	∼175	∼655	∼95	∼1110	∼161	∼960	∼139	∼565	∼82	∼12	∼11	∼20
Incoloy 909	Bar	1310	190	1160	168	615	89	1020	148	945	137	540	78	16	14	34
N-155	Bar	815	118	650	94	428	62	400	58	340	49	250	36	40	33	32
V-57	Bar	1170	170	1000	145	620	90	830	120	760	110	485	70	26	19	34
19-9 DL(g)	. . .	815	118	615	89	. . .	. . .	570	83	395	57	. . .	. . .	43	30	. . .
16-25-6(g)	. . .	980	142	. . .	. . .	415	60	770	112	. . .	. . .	345	50	23	. . .	11
Cobalt-base																
AirResist 213(h)	. . .	1120	162	. . .	. . .	485	70	625	91	. . .	. . .	385	56	14	. . .	47
Elgiloy(h)	. . .	690(e)-2480(i)	100(e)-360(i)	. . .	. . .	. . .	. . .	480(e)-2000(i)	70-290	. . .	. . .	. . .	. . .	34	. . .	. . .
Haynes 188	Sheet	960	139	740	107	635	92	485	70	305	44	290	42	56	70	43
L-605	Sheet	1005	146	800	116	455	66	460	67	250	36	260	38	64	59	12
MAR-M 918	Sheet	895	130	. . .	. . .	. . .	. . .	895	130	. . .	. . .	. . .	. . .	48	. . .	. . .
MP35N	Bar	2025	294	. . .	. . .	. . .	. . .	1620	235	. . .	. . .	. . .	. . .	10	. . .	. . .
MP159	Bar	1895	275	1565	227	. . .	. . .	1825	265	1495	217	. . .	. . .	8	8	. . .
Stellite 6B(h)	Sheet	1010	146	. . .	. . .	. . .	. . .	635	92	. . .	. . .	. . .	. . .	11	. . .	. . .

Haynes 150[h]	. . .	925	134	. . .	. . .	. . .	. . .	317	46	. . .	. . .	. . .	. . .	8	. . .	. . .

Source: Ref 12, except as noted

(a) Cold-rolled and solution-annealed sheet, 1.2 to 1.6 mm (0.048 to 0.063 in.) thick.

(b) Ref 11.

(c) Ref 7.

(d) Ref 8.

(e) Annealed.

(f) Precipitation hardened.

(g) Ref 9.

(h) Ref 10.

(i) Work strengthened and aged.

Table 8 1000 h rupture strengths of wrought nickel-, cobalt-, and iron-base superalloys

Alloy	Form	Rupture strength at:							
		650 °C (1200 °F)		**760 °C (1400 °F)**		**870 °C (1600 °F)**		**980 °C (1800 °F)**	
		MPa	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**
Nickel-base									
Astroloy	Bar	770	112	425	62	170	25	55	8
Cabot 214	. . .	. . .	. . .	. . .	. . .	30	4	15	2
D-979	Bar	515	75	250	36	70	10	. . .	. . .
Hastelloy S	Bar	. . .	. . .	90	13	25	4	. . .	. . .

Hastelloy X	Sheet	215	31	105	15	40	6	15	2
Haynes 230	. . .	. . .	. . .	125	18	55	8	15	2
Inconel 587[(a)]	Bar	. . .	. . .	285	41	. . .	. . .	. . .	. . .
Inconel 597[(a)]	Bar	. . .	. . .	340	49	. . .	. . .	. . .	. . .
Inconel 600	Bar	. . .	. . .	. . .	. . .	30	4	15	2
Inconel 601	Sheet	195	28	60	9	30	4	15	2
Inconel 617	Bar	360	52	165	24	60	9	30	4
Inconel 617	Sheet	. . .	. . .	160	23	60	9	30	4
Inconel 625	Bar	370	54	160	23	50	7	20	3
Inconel 706	Bar	580	84	. . .	. . .	. . .	. . .	. . .	. . .
Inconel 718	Bar	595	86	195	28	. . .	. . .	. . .	. . .
Inconel 718 Direct Age	Bar	405	59	. . .	. . .	. . .	. . .	. . .	. . .
Inconel 718 Super	Bar	600	87	. . .	. . .	. . .	. . .	. . .	. . .
Inconel X750	Bar	470	68	. . .	. . .	50	7	. . .	. . .
M-252	Bar	565	82	270	39	95	14	. . .	. . .
Nimonic 75	Bar	170	25	50	7	5	1	. . .	. . .
Nimonic 80A	Bar	420	61	160	23	. . .	. . .	. . .	. . .
Nimonic 90	Bar	455	66	205	30	60	9	. . .	. . .
Nimonic 105	Bar	. . .	. . .	330	48	130	19	30	4
Nimonic 115	Bar	. . .	. . .	420	61	185	27	70	10
Nimonic 942[(a)]	Bar	520	75	270	39	. . .	. . .	. . .	. . .

Nimonic PE.11[(a)]	Bar	335	49	145	21	. . .	. . .	. . .	. . .
Nimonic PE.16	Bar	345	50	150	22	. . .	. . .	. . .	. . .
Nimonic PK.33	Sheet	655	95	310	45	90	13	. . .	. . .
Pyromet 860[(a)]	Bar	545	79	250	36	. . .	. . .	. . .	. . .
René 41	Bar	705	102	345	50	115	17	. . .	. . .
René 95	Bar	860	125	. . .	. . .	. . .	. . .	. . .	. . .
Udimet 400[(a)]	Bar	600	87	305	44	110	16	. . .	. . .
Udimet 500	Bar	760	110	325	47	125	18	. . .	. . .
Udimet 520	Bar	585	85	345	50	150	22	. . .	. . .
Udimet 700	Bar	705	102	425	62	200	29	55	8
Udimet 710	Bar	870	126	460	67	200	29	70	10
Udimet 720	Bar	670	97	. . .	. . .	. . .	. . .	. . .	. . .
Unitemp AF2-1DA6	Bar	885	128	360	52	. . .	. . .	. . .	. . .
Waspaloy	Bar	615	89	290	42	110	16	. . .	. . .
Iron-base									
A-286	Bar	315	46	105	15	. . .	. . .	. . .	. . .
Alloy 901	Sheet	525	76	205	30	. . .	. . .	. . .	. . .
Discaloy	Bar	275	40	60	9	. . .	. . .	. . .	. . .
Haynes 556	Sheet	275	40	125	18	55	8	20	3
Incoloy 800[(a)]	Bar	165	24	66	9.5	30	4.4	13	1.9
Incoloy 801[(a)]	Bar	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

Incoloy 802[(a)]	Bar	170	25	110	16	69	10	24	3.5
Incoloy 807[(a)]	Bar	. . .	. . .	105	15	43	6.2	19	2.7
Incoloy 903	Bar	510	74	. . .	. . .	. . .	. . .	. . .	. . .
Incoloy 909	Bar	345	50	. . .	. . .	. . .	. . .	. . .	. . .
N-155	Bar	295	43	140	20	70	10	20	3
V-57	Bar	485	70	. . .	. . .	. . .	. . .	. . .	. . .
Cobalt-base									
Haynes 188	Sheet	. . .	. . .	165	24	70	10	30	4
L-605	Sheet	270	39	165	24	75	11	30	4
MAR-M 918	Sheet	. . .	. . .	60	9	20	3	5	1
Haynes 150[(b)]	. . .	. . .	. . .	40[(c)]	5.8	. . .	. . .	. . .	. . .

Source: Ref 12, except as noted

(a) Ref 7.

(b) Ref 9.

(c) At 815 °C (1500 °F).

Table 9 Effect of temperature on the mechanical properties of cast nickel-base and cobalt-base alloys

Alloy	Ultimate tensile strength at:						0.2% yield strength at:						Tensile elongation, % at:		
	21 °C (70 °F)		**538 °C (1000 °F)**		**1093 °C (2000 °F)**		**21 °C (70 °F)**		**538 °C (1000 °F)**		**1093 °C (2000 °F)**		**21 °C (70 °F)**	**538 °C (1000 °F)**	**1093 °C (2000 °F)**
	MPa	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**			
Nickel-base															
IN-713 C	850	123	860	125	. . .	. . .	740	107	705	102	. . .	. . .	8	10	. . .

IN-713 LC	895	130	895	130	. . .	. . .	750	109	760	110	. . .	. . .	15	11	. . .
B-1900	970	141	1005	146	270	38	825	120	870	126	195	28	8	7	11
IN-625	710	103	510	74	. . .	. . .	350	51	235	34	. . .	. . .	48	50	. . .
IN-718	1090	158	. . .	. . .	. . .	. . .	915	133	. . .	. . .	. . .	. . .	11	. . .	. . .
IN-100	1018	147	1090	150	(380)	(55)	850	123	885	128	(240)	(35)	9	9	. . .
IN-162	1005	146	1020	148	. . .	. . .	815	118	795	115	. . .	. . .	7	6.5	. . .
IN-731	835	121	. . .	. . .	275	40	725	105	. . .	. . .	170	25	6.5	. . .	. . .
IN-738	1095	159	. . .	. . .	. . .	. . .	950	138	. . .	. . .	. . .	. . .	. . .	. . .	. . .
IN-792	1170	170	. . .	. . .	. . .	. . .	1060	154	. . .	. . .	. . .	. . .	4	. . .	. . .
M-22	730	106	780	113	. . .	. . .	685	99	730	106	. . .	. . .	5.5	4.5	. . .
MAR-M 200	930	135	945	137	325	47	840	122	880	123	. . .	. . .	7	5	. . .
MAR-M 246	965	140	1000	145	345	50	860	125	860	125	. . .	. . .	5	5	. . .
MAR-M 247	965	140	1035	150	. . .	. . .	815	118	825	120	. . .	. . .	7	. . .	. . .
MAR-M 421	1085	157	995	147	. . .	. . .	930	135	815	118	. . .	. . .	4.5	3	. . .
MAR-M 432	1240	180	1105	160	. . .	. . .	1070	155	910	132	. . .	. . .	6	. . .	. . .
MC-102	675	98	655	95	. . .	. . .	605	88	540	78	. . .	. . .	5	9	. . .
Nimocast 75	500	72	. . .	. . .	. . .	. . .	179	26	. . .	. . .	. . .	. . .	39	. . .	. . .
Nimocast 80	730	106	. . .	. . .	. . .	. . .	520	75	. . .	. . .	. . .	. . .	15	. . .	. . .
Nimocast 90	700	102	595	86	. . .	. . .	520	75	420	61	. . .	. . .	14	15	. . .
Nimocast 242	460	67	. . .	. . .	. . .	. . .	300	44	. . .	. . .	. . .	. . .	8	. . .	. . .

Nimocast 263	730	106	. . .	. . .	. . .	. . .	510	74	. . .	. . .	. . .	. . .	18	. . .	. . .
René 77	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
René 80	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Udimet 500	930	135	895	130	. . .	. . .	815	118	725	105	. . .	. . .	13	13	. . .
Udimet 710	1075	156	. . .	. . .	240	35	895	130	. . .	. . .	170	25	8	. . .	. . .
CMSX-2(a)(b)	1185	172	1295(c)	188(c)	. . .	. . .	1135	165	1245(c)	181(c)	. . .	. . .	10	17(c)	. . .
GMR-235(b)	710	103	. . .	. . .	. . .	. . .	640	93	. . .	. . .	. . .	. . .	3	. . .	18(d)
IN-939(b)	1050	152	915(c)	133(c)	325(d)	47(d)	800	116	635(c)	92(c)	205(d)	30(d)	5	7(c)	25(d)
MM 002(b)(e)	1035	150	1035(c)	150(c)	550(d)	80(d)	825	120	860(c)	125(c)	345(d)	50(d)	7	5(c)	12(d)
IN-713 Hf(b)(f)	1000	145	895(c)	130(c)	380(d)	55(d)	760	110	620(c)	90(c)	240(d)	35(d)	11	6(c)	20(d)
René 125 Hf(b)(g)	1070	155	1070(c)	155(c)	550(d)	80(d)	825	120	860(c)	125(c)	345(d)	50(d)	5	5(c)	12(d)
MAR-M 246 Hf(b)(h)	1105	160	1070(c)	155(c)	565(d)	82(d)	860	125	860(c)	125(c)	345(d)	50(d)	6	7(c)	14(d)
MAR-M 200 Hf(b)(i)	1035	150	1035(c)	150(c)	540(d)	78(d)	825	120	860(c)	125(c)	345(d)	50(d)	5	5(c)	10(d)
PWA-1480(a)(b)	. . .	. . .	1130(c)	164(c)	685(d)	99(d)	895	130	905(c)	131(c)	495(d)	72(d)	4	8(c)	20(d)
SEL(b)	1020	148	875(c)	127(c)	. . .	. . .	905	131	795(c)	115(c)	. . .	. . .	6	7(c)	. . .
UDM 56(b)	945	137	945(c)	137(c)	. . .	. . .	850	123	725(c)	105(c)	. . .	. . .	3	5(c)	. . .
SEL-15(b)	1060	154	1090(c)	158(c)	. . .	. . .	895	130	815(c)	118(c)	. . .	. . .	9	5(c)	. . .
Cobalt-base															
AiResist 13(j)	600	87	420(c)	61(c)	. . .	. . .	530	77	330(c)	48(c)	. . .	. . .	1.5	4.5(c)	. . .

AiResist 215(j)	690	100	570(k)	83(k)	. . .	. . .	485	70	315(k)	46(k)	. . .	. . .	4	12(k)	. . .
FSX-414	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Haynes 1002	770	112	560	81	115	17	470	68	345	50	95	14	6	8	28
MAR-M 302	930	135	795	115	150	22	690	100	505	73	150	22	2	. . .	21
MAR-M 322(j)	830	120	595(c)	86(c)	. . .	. . .	630	91	345(c)	50(c)	. . .	. . .	4	6.5(c)	. . .
MAR-M 509	785	114	570	83	. . .	. . .	570	83	400	58	. . .	. . .	4	6	. . .
WI-52	750	109	745	108	160	23	585	85	440	64	105	15	5	7	35
X-40	745	108	550	80	. . .	. . .	525	76	275	40	. . .	. . .	9	17	. . .

Source: Nickel Development Institute, except as noted

(a) Single crystal [001].

(b) Data from Ref 12.

(c) At 760 °C (1400 °F).

(d) At 980 °C (1800 °F).

(e) RR-7080.

(f) MM 004.

(g) M 005.

(h) MM 006.

(i) MM 009.

(j) Data from Vol 3, 9th ed., *Metals Handbook,* 1980.

(k) At 650 °C (1200 °F).

Table 10 Stress-rupture strengths for selected cast nickel-base superalloys

Alloy	Rupture stress at:					
	815 °C (1500 °F)		**870 °C (1600 °F)**		**980 °C (1800 °F)**	
	100 h MPa (ksi)	**1000 h MPa (ksi)**	**100 h MPa (ksi)**	**1000 h MPa (ksi)**	**100 h MPa (ksi)**	**1000 h MPa (ksi)**
Nickel-base						
IN-713 LC	425 (62)	325 (47)	295 (43)	240 (35)	140 (20)	105 (15)
IN-713 C	370 (54)	305 (44)	305 (44)	215 (31)	130 (19)	70 (10)
IN-738 C	470 (68)	345 (50)	330 (48)	235 (34)	130 (19)	90 (13)
IN-738 LC	430 (62)[a]	315 (46)	295 (43)[a]	215 (31)	140 (20)[a]	90 (13)
IN-100	455 (66)	365 (53)	360 (52)	260 (38)	160 (23)	90 (13)
MAR-M 247 (MM 0011)	585 (85)	415 (60)	455 (66)	290 (42)	185 (27)	125 (18)
MAR-M 246[a]	525 (76)	435 (62)	440 (63)	290 (42)	195 (28)	125 (18)
MAR-M 246 Hf (MM 006)	530 (77)	425 (62)	425 (62)	285 (41)	205 (30)	130 (19)
MAR-M 200	495 (72)[a]	415 (60)[a]	385 (56)[a]	295 (43)[a]	170 (25)	125 (18)
MAR-M 200 Hf (MM 009)[b]	. . .	. . .	. . .	305 (44)	. . .	125 (18)
B-1900	510 (74)	380 (55)	385 (56)	250 (36)	180 (26)	110 (16)
René 77[a]	. . .	. . .	310 (45)	215 (31.5)	130 (19)	62 (9.0)
René 80	. . .	. . .	350 (51)	240 (35)	160 (23)	105 (15)
IN-625[a]	130 (19)	110 (16)	97 (14)	76 (11)	34 (5)	28 (4)
IN-162[a]	505 (73)	370 (54)	340 (49)	255 (37)	165 (24)	110 (16)

IN-731(a)	505 (73)	365 (53)	. . .	. . .	165 (24)	105 (15)
IN-792(a)	515 (75)	380 (55)	365 (53)	260 (38)	165 (24)	105 (15)
M-22(a)	515 (75)	385 (56)	395 (57)	285 (41)	200 (29)	130 (19)
MAR-M 421(a)	450 (65)	305 (44)	310 (46)	215 (31)	125 (18)	83 (12)
MAR-M 432(a)	435 (63)	330 (48)	295 (40)	215 (31)	140 (20)	97 (14)
MC-102(a)	195 (28)	145 (21)	145 (21)	105 (15)	. . .	. . .
Nimocast 90(a)	160 (23)	110 (17)	125 (18)	83 (12)	. . .	. . .
Nimocast 242(a)	110 (16)	83 (12)	90 (13)	59 (8.6)	45 (6.5)	. . .
Udimet 500(a)	330 (48)	240 (35)	230 (33)	165 (24)	90 (13)	. . .
Udimet 710(a)	420 (61)	325 (47)	305 (44)	215 (31)	150 (22)	76 (11)
CMSX-2(b)	. . .	. . .	. . .	345 (50)	. . .	170 (25)
GMR-235(b)	. . .	. . .	. . .	180 (26)	. . .	75 (11)
IN-939(b)	. . .	. . .	. . .	195 (28)	. . .	60 (9)
MM 002(b)	. . .	. . .	. . .	305 (44)	. . .	125 (18)
IN-713 Hf (MM 004)(b)	. . .	. . .	. . .	205 (30)	. . .	90 (13)
René 125 Hf (MM 005)(b)	. . .	. . .	. . .	305 (44)	. . .	115 (17)
SEL-15(b)	. . .	. . .	. . .	295 (43)	. . .	75 (11)
UDM 56(b)	. . .	. . .	. . .	270 (39)	. . .	125 (18)
Cobalt-base						
HS-21	150 (22)	95 (14)	115 (17)	90 (13)	60 (9)	50 (7)
X-40 (HS-31)	180 (26)	140 (20)	130 (19)	105 (15)	75 (11)	55 (8)

MAR-M 509	270 (39)	225 (33)	200 (29)	140 (20)	115 (17)	90 (13)
FSX-414	150 (22)	115 (17)	110 (16)	85 (12)	55 (8)	35 (5)
WI-52	. . .	195 (28)	175 (25)	150 (22)	90 (13)	70 (10)

(a) Ref 12.

(b) Ref 13

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Environmental Effects

General Oxidation

Superalloys generally react with oxygen, and oxidation is the prime environmental effect on these alloys. At moderate temperatures--approximately 870 °C (1600 °F) and below--general uniform oxidation is not a major problem. At higher temperatures, commercial nickel- and cobalt-base superalloys are attacked by oxygen. The level of oxidation resistance at temperatures below approximately 980 °C (1800 °F) is a function of chromium content (Cr_2O_3 forms as a protective oxide); at temperatures above approximately 980 °C (1800 °F), aluminum content becomes more important in oxidation resistance (Al_2O_3 forms as a protective oxide). Chromium and aluminum can contribute in an interactive fashion to oxidation protection. The higher the chromium level, the less aluminum may be required to form a highly protective Al_2O_3 layer. However, the aluminum contents of many superalloys are insufficient to provide long-term Al_2O_3 protection, and so protective coatings are applied (see below). These coatings also prevent selective attack that occurs along grain boundaries and at surface carbides (Fig. 21) and inhibit internal oxidation or subsurface interaction of O_2/N_2 with γ' envelopes, a process believed to occur in nickel-base superalloys.

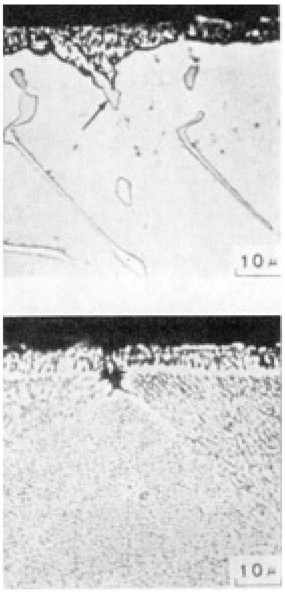


Fig. 21 Effects of oxidation on superalloys. (a) Accelerated oxidation of MC carbide (arrow) at surface of MAR-M 200 at 925 °C (1700 °F). (b) Accelerated oxidation of grain boundary in Udimet 700 at 760 °C (1400 °F). 1000×

Hot Corrosion

In lower temperature operating conditions, $\leq$870 °C ($\leq$1600 °F), accelerated oxidation in a gas path may occur in superalloys through the operation of selective fluxing agents. One of the better-documented accelerated oxidation processes is hot corrosion (sometimes known as sulfidation). The hot corrosion process is separated into two regimes: low temperature and high temperature. The principal method for combating hot corrosion is the use of a high chromium content ($\geq$20 wt%) in the base alloy. Although cobalt-base superalloys and many iron-nickel-base alloys have chromium levels in this range, most nickel-base alloys--especially those with high creep-rupture strengths--do not, because a high chromium content is not compatible with the high $V_f \gamma'$ required.

Higher titanium/aluminum ratios also seem to reduce attack on uncoated superalloys, and alloys with improved resistance to hot corrosion, based on slightly increased chromium contents and appropriate titanium/aluminum modifications, have been produced. For maximum uncoated hot-corrosion resistance, however, chromium contents in excess of 20 wt% appear to be required. Such alloys are not capable of achieving the strengths of the high $V_f \gamma'$ alloys such as MAR-M 247. Consequently, coatings that protect the base metal (overlay coatings seem to provide the best surface protection), or sometimes environmental inhibitors, are used to suppress hot-corrosion attack in high-strength (high $V_f \gamma'$) nickel-base superalloys.

Coatings

Development of increased strength (increased $V_f \gamma'$) in nickel-base superalloys led to reductions in chromium content and to greater oxidation attack and susceptibility to hot corrosion. Although aluminum contents of some alloys were increased in order to enhance resistance to oxidation, intergranular and carbide attack worsened as operating temperatures escalated. Furthermore, some of the more oxidation-resistant alloys were found to be very poor in hot-corrosion resistance. To protect against local oxidation, and later, against hot corrosion and similar fluxing reactions, coatings were applied to superalloys. In recent years, thermal barrier coatings (TBCs) have been developed to provide substantial reductions in temperatures on superalloy surfaces. These coatings are commonly used in conjunction with corrosion protective coatings.

Coatings are of two types: aluminide (diffusion) coatings and overlay coatings. Use of coatings is a preferred method of protecting superalloy surfaces from environmental attack because:

- Coatings (at least overlay coatings) can be tailored to the hostile environment anticipated.
- Development of base alloys for strength is less inhibited, because significant protection (but not all of the protection) is provided by the coating.
- Coatings provide an opportunity to refurbish worn surfaces after exposure and environmental attack without causing significant degradation of the base metal.

Aluminide (Diffusion) Coatings. The most common type of coating for environmental protection of superalloys is the aluminide diffusion coating, which develops an aluminide (CoAl or NiAl) outer layer with enhanced oxidation resistance. This outer layer is developed by the reaction of aluminum with the nickel or cobalt in the base metal.

Some use has been made of aluminides containing chromium or silicon, and in recent years noble metals such as platinum have been used to enhance the oxidation resistance of aluminides. The oxidation resistance of aluminide coatings is derived from formation of protective Al_2O_3 scales. Aluminide diffusion coatings generally are thin--about 50 to 75 μm (2 to 3 mils). They consume some base metal in their formation and, although deposited at lower temperatures, are invariably diffused at temperatures from approximately 1040 to 1120 °C (1900 to 2050 °F) prior to being placed in service.

Overlay coatings generally are referred to as MCrAl or MCrAlY coatings, and are derived directly from the deposition process. They do not require diffusion for their formation. The constituent denoted "M" in these designations has at various times been iron, cobalt, nickel, or combinations of nickel and cobalt. A high-temperature heat treatment (at 1040 to 1120 °C, or 1900 to 2050 °F) is performed to homogenize the coating and to ensure its adherence to the substrate.

MCrAl coatings are approximately twice as thick as aluminide coatings, and, through incorporation of yttrium, overlay coatings can be made to have improved corrosion resistance. An advantage of MCrAlY coatings is that their compositions can be tailored to produce greater or lesser amounts of chromium or aluminum within the coating, and thus the protectivity and mechanical properties of the coating can be balanced for optimum performance.

Thermal barrier coatings have provided enough insulation for superalloys to operate in temperature environments as much as 165 °C (300 °F) above their customary operating range. The TBCs are ceramics, most notably plasma-sprayed partially stabilized zirconia (PSZ). These ceramic coatings use an underlay of a corrosion-protective layer--typically an overlay coating such as an MCrAlY that provides for oxidation resistance and the necessary roughness for top-coat adherence. Thermal barrier coatings do not provide oxidation protection for superalloys.

Effects of Coatings on Mechanical Behavior. Coatings seem to have little deleterious effect on tensile and creep-rupture properties. In fact, creep-rupture life may be enhanced by protection of the superalloy surface from oxidation or fluxing-agent attack. Thermomechanical fatigue can be greatly affected by a coating because the ductilities of coatings tend to be low at low temperatures. Ductilities of aluminide coatings generally are lower than those of overlay coatings at lower temperatures ($\leq$540 °C, or 1000 °F). However, ductilities of both overlay and diffusion coatings increase sharply at higher temperatures ($\geq$650 °C, or 1200 °F). When TMF cycles have peak tensile strains at lower temperatures, coatings may crack within the first few cycles, and TMF response is related to the crack-propagation rate in the base metal. Some adjustment of ductility is possible, particularly in the overlay coatings. However, because aluminum--the protective element--is a principal cause of reduced ductility, a balance must be achieved between protectivity and resistance to TMF.

Coating Processes. Aluminide diffusion coatings generally are applied by pack processes, but slurry, electrophoretic, and other techniques also have been used. Customarily, deposition is done at an intermediate temperature, followed by diffusion in a controlled-atmosphere furnace at approximately 1040 to 1120 °C (1900 to 2050 °F).

Overlay coatings are applied by physical vapor deposition (PVD) in vacuum chambers. They also may be applied by plasma spray techniques. Low-pressure plasma spray (LPPS) techniques produce coatings with properties comparable to or better than those of PVD vacuum-produced coatings. (Argon is used in LPPS, in opposition to the air plasma-spray process originally used.) Low-pressure plasma spray has been one of the primary methods of applying TBCs.

Overlay coatings tend to be line-of-sight coatings, whereas pack-diffusion coatings are not. Plasma spray techniques afford more flexibility in application of overlay coatings than do PVD processes, because the angular relationship between the plasma and the part may be varied more or less in a large envelope in order to direct the coating to desired areas. Plasma spray also provides more opportunity for compositional flexibility than does PVD.

General Requirements of a Corrosion Protective Coating. Coating selection will be based on knowledge of oxidation/corrosion behavior in laboratory, pilot-plant, and field tests. Attributes that probably will be required for successful coating selection include:

- High resistance to oxidation and/or hot corrosion
- Ductility sufficient to provide adequate resistance to TMF
- Compatibility with the base alloys
- Low rate of interdiffusion with the base alloy
- Ease of application and low cost relative to improvement in component life
- Ability to be stripped and reapplied without significant reduction of base-metal dimensions or degradation of base-metal properties

Other Environmental Effects

Stress-corrosion cracking can occur in nickel-and iron-nickel-base superalloys at lower temperatures. Hydrogen embrittlement at cryogenic temperatures has been reported for such alloys. Furthermore, so-called inert environments--vacuum, for example, or gases such as helium or argon--may produce mechanical behavior substantially different from baseline uncoated properties, which usually are determined in static-air tests.

Introduction to Aluminum and Aluminum Alloys

Introduction

THE UNIQUE COMBINATIONS of properties provided by aluminum and its alloys make aluminum one of the most versatile, economical, and attractive metallic materials for a broad range of uses--from soft, highly ductile wrapping foil to the most demanding engineering applications. Aluminum alloys are second in use only to steels as structural metals.

Aluminum has a density of only 2.7 g/cm^3, approximately one-third as much as steel (7.83 g/cm^3). One cubic foot of steel weighs about 490 lb; a cubic foot of aluminum, only about 170 lb. Such light weight, coupled with the high strength of some aluminum alloys (exceeding that of structural steel), permits design and construction of strong, lightweight structures that are particularly advantageous for anything that moves--space vehicles and aircraft as well as all types of land- and water-borne vehicles.

Aluminum resists the kind of progressive oxidization that causes steel to rust away. The exposed surface of aluminum combines with oxygen to form an inert aluminum oxide film only a few ten-millionths of an inch thick, which blocks further oxidation. And, unlike iron rust, the aluminum oxide film does not flake off to expose a fresh surface to further oxidation. If the protective layer of aluminum is scratched, it will instantly reseal itself.

The thin oxide layer itself clings tightly to the metal and is colorless and transparent--invisible to the naked eye. The discoloration and flaking of iron and steel rust do not occur on aluminum.

Appropriately alloyed and treated, aluminum can resist corrosion by water, salt, and other environmental factors, and by a wide range of other chemical and physical agents. The corrosion characteristics of aluminum are examined in detail in the article "Corrosion Resistance of Aluminum and Aluminum Alloys" in this Section.

Aluminum surfaces can be highly reflective. Radiant energy, visible light, radiant heat, and electromagnetic waves are efficiently reflected, while anodized and dark anodized surfaces can be reflective or absorbent. The reflectance of polished aluminum, over a broad range of wave lengths, leads to its selection for a variety of decorative and functional uses.

Aluminum typically displays excellent electrical and thermal conductivity, but specific alloys have been developed with high degrees of electrical resistivity. These alloys are useful, for example, in high-torque electric motors. Aluminum is often selected for its electrical conductivity, which is nearly twice that of copper on an equivalent weight basis. The requirements of high conductivity and mechanical strength can be met by use of long-line, high-voltage, aluminum steel-cored reinforced transmission cable. The thermal conductivity of aluminum alloys, about 50 to 60% that of copper, is advantageous in heat exchangers, evaporators, electrically heated appliances and utensils, and automotive cylinder heads and radiators.

Aluminum is nonferromagnetic, a property of importance in the electrical and electronics industries. It is nonpyrophoric, which is important in applications involving inflammable or explosive-materials handling or exposure. Aluminum is also non-toxic and is routinely used in containers for food and beverages. It has an attractive appearance in its natural finish, which can be soft and lustrous or bright and shiny. It can be virtually any color or texture.

The ease with which aluminum may be fabricated into any form is one of its most important assets. Often is can compete successfully with cheaper materials having a lower degree of workability. The metal can be cast by any method known to foundrymen. It can be rolled to any desired thickness down to foil thinner than paper. Aluminum sheet can be stamped, drawn, spun, or roll formed. The metal also may be hammered or forged. Aluminum wire, drawn from rolled rod, may be stranded into cable of any desired size and type. There is almost no limit to the different profiles (shapes) in which the metal can be extruded.

The Aluminum Industry

Primary Production. All aluminum production is based on the Hall-Héroult process. Alumina refined from bauxite is dissolved in a cryolite bath with various fluoride salt additions made to control bath temperature, density, resistivity, and alumina solubility. An electrical current is then passed through the bath to electrolyze the dissolved alumina with oxygen forming at and reacting with the carbon anode, and aluminum collecting as a metal pad at the cathode. The separated metal is periodically removed by siphon or vacuum methods into crucibles, which are then transferred to casting facilities where remelt or fabricating ingots are produced.

The major impurities of smelted aluminum are iron and silicon, but zinc, gallium, titanium, and vanadium are typically present as minor contaminants. Internationally, minimum aluminum purity is the primary criterion for defining composition and value. In the United States, a convention for considering the relative concentrations of iron and silicon as the more important criteria has evolved. Reference to grades of unalloyed metal may therefore be by purity alone, for example, 99.70% aluminum, or by the method sanctioned by the Aluminum Association in which standardized P*xxx* grades have been established. In the latter case, the digits following the letter P refer to the maximum decimal percentages of silicon and iron, respectively. For example, P1020 is unalloyed smelter-produced metal containing no more than 0.10% Si and no more than 0.20% Fe. P0506 is a grade that contains no more than 0.05% Si and no more than 0.06% Fe. Common P grades range from P0202 to P1535, each of which incorporates additional impurity limits for control purposes.

Refining steps are available to attain much higher levels of purity. Purities of 99.99% are achieved through fractional crystallization or Hoopes cell operation. The latter process is a three-layer electrolytic process which employs molten salt of greater density than pure molten aluminum. Combinations of these purification techniques result in 99.999% purity for highly specialized applications.

Secondary Aluminum. Aluminum recovered from scrap (secondary aluminum) has been an important contributor to the total metal supply for many years. New scrap is defined as that generated by plants making end products, whereas old scrap is that recovered from metal that has been previously used by consumers. In addition, considerable amounts of scrap generated at various stages of mill processing are recycled. The increased concern with and economic implications of energy supply in recent years have focused even more attention on recycling of aluminum because of its energy-intensive nature. The energy required to remelt secondary aluminum preparatory to fabrication for reuse is only 5% of that required to produce new aluminum. Consequently, recycling is increasing. In particular, recovery of used aluminum beverage containers has multiplied many times in the last 20 years. In 1996, some 893 thousand metric tons of used beverage cans were collected in the United States. This constitutes 63.5% of can shipments. In some countries, for example Sweden, recycling rates exceeding 80% are achieved.

For some uses, secondary aluminum alloys may be treated to remove certain impurities or alloying elements. Chief among the alloying elements removed is magnesium, which is frequently present in greater amounts in secondary metal than in the alloys to be produced from it. Magnesium is usually removed by fluxing with chlorine gas or halide salts. More detailed information on secondary recovery of aluminum is included in the Section "Recycling and Life-Cycle Analysis" in this Handbook.

Production and Markets. World production of primary aluminum totaled 20,670 thousand metric tons in 1996. Over the decade 1986-1996, world production increased at an annual growth rate of 2.1%. The United States accounted for 17.3% of the world's 1996 production while the European Union accounted for 10.7%. Other European countries, including former members of the Union of Soviet Socialist Republics, accounted for 20.7%. The remaining production includes Asia (17.5%), Canada (11%), Latin America (9.8%), Oceania (8%), and Africa (5%).

The total United States supply in 1996 was 9,434 thousand metric tons. Since 1986, the total supply has expanded at an average of 3.6% a year. In 1996, primary production accounted for 37.9% of the total supply, imports 27.3%, and secondary recovery 34.8%.

Sheet, plate, and foil constitute the major share of total U.S. aluminum product shipments, followed by ingot for castings, export, and other uses. A percentage distribution of major aluminum products is presented below:

Product form	Distribution, %
Sheet, plate, and foil	51.3
Ingot	26.4
Extrusions and tube	14.9
Other(a)	7.4

Source: The Aluminum Association Inc.

(a) Includes conductor (3.0%); rod, bar, and wire (2.7%); forgings and impacts (1.1%); and powder (0.6%).

In decreasing order of current market size, the major application categories are transportation (27.6%), containers and packaging (22.8%), building and construction (13.7%), exports (13.5%), electrical (7.0%), consumer durables (6.6%), machinery and equipment (5.9%), and others (2.9%).

Aluminum Alloys

The mechanical, physical, and chemical properties of aluminum alloys depend upon composition and microstructure. The addition of selected elements to pure aluminum greatly enhances its properties and usefulness. Because of this, most applications for aluminum utilize alloys having one or more elemental additions. The major alloying additions used with aluminum are copper, manganese, silicon, magnesium, and zinc. The total amount of these elements can constitute up to 10% of the alloy composition (all percentages given in weight percent unless otherwise noted). Impurity elements are also present, but their total percentage is usually less than 0.15% in aluminum alloys.

It is convenient to divide aluminum alloys into two major categories: wrought compositions and cast compositions. A further differentiation for each category is based on the primary mechanism of property development. Many alloys respond to thermal treatment based on phase solubilities. These treatments include solution heat treatment, quenching, and precipitation, or age, hardening. For either casting or wrought alloys, such alloys are described as heat treatable. A large number of other wrought compositions rely instead on work hardening through mechanical reduction, usually in combination with various annealing procedures for property development. These alloys are referred to as work hardening. Some casting alloys are essentially not heat treatable and are used only in as-cast or in thermally modified conditions unrelated to solution or precipitation effects.

Cast and wrought alloy nomenclatures have been developed. The Aluminum Association system is most widely recognized in the United States. Their alloy identification system employs different nomenclatures for wrought and cast alloys, but divides alloys into families for simplification (see the article "Alloy and Temper Designation Systems for Aluminum" in this Section for details). For wrought alloys a four-digit system is used to produce a list of wrought composition families as follows:

- 1*xxx*: Controlled unalloyed (pure) composition, used primarily in the electrical and chemical industries
- 2*xxx*: Alloys in which copper is the principal alloying element, although other elements, notably magnesium, may be specified. 2*xxx*-series alloys are widely used in aircraft where their high strength (yield strengths as high as 455 MPa, or 66 ksi) are valued.
- 3*xxx*: Alloys in which manganese is the principal alloying element, used as general-purpose alloys for architectural applications and various products
- 4*xxx*: Alloys in which silicon is the principal alloying element, used in welding rods and brazing sheet
- 5*xxx*: Alloys in which magnesium is the principal alloying element, used in boat hulls, gangplanks, and other products exposed to marine environments
- 6*xxx*: Alloys in which magnesium and silicon are the principal alloying elements, commonly used for architectural extrusions
- 7*xxx*: Alloys in which zinc is the principal alloying element (although other elements, such as copper, magnesium, chromium, and zirconium, may be specified), used in aircraft structural components and other high-strength applications. The 7*xxx* series are the strongest aluminum alloys, with yield strengths ≥500 MPa (≥73 ksi) possible.
- 8*xxx*: Alloys characterizing miscellaneous compositions. The 8*xxx* series alloys may contain appreciable amounts of tin, lithium, and/or iron.
- 9*xxx*: Reserved for future use

Wrought alloys that constitute heat-treatable (precipitation-hardenable) aluminum alloys include the 2*xxx*, 6*xxx*, 7*xxx*, and some of the 8*xxx* alloys. The various combinations of alloying additions and strengthening mechanisms used for wrought aluminum alloys are shown in Table 1. The strength ranges achievable with various classes of wrought alloys are given in Table 2. More detailed information on the strengthening mechanisms associated with aluminum alloys can be found in the article "Physical Metallurgy of Aluminum Alloys" in this Section.

Table 1 Classification of wrought aluminum alloys according to their strengthening mechanism

Alloy system	Aluminum series
Work-hardenable alloys	
Pure Al	1*xxx*
Al-Mn	3*xxx*
Al-Si	4*xxx*

Al-Mg	5*xxx*
Al-Fe	8*xxx*
Al-Fe-Ni	8*xxx*
Precipitation-hardenable alloys	
Al-Cu	2*xxx*
Al-Cu-Mg	2*xxx*
Al-Cu-Li	2*xxx*
Al-Mg-Si	6*xxx*
Al-Zn	7*xxx*
Al-Zn-Mg	7*xxx*
Al-Zn-Mg-Cu	7*xxx*
Al-Li-Cu-Mg	8*xxx*

Table 2 Strength ranges of various wrought aluminum alloys

Aluminum Association series	Type of alloy composition	Strengthening method	Tensile strength range	
			MPa	**ksi**
1*xxx*	Al	Cold work	70-175	10-25
2*xxx*	Al-Cu-Mg (1-2.5% Cu)	Heat treat	170-310	25-45
2*xxx*	Al-Cu-Mg-Si (3-6% Cu)	Heat treat	380-520	55-75
3*xxx*	Al-Mn-Mg	Cold work	140-280	20-40
4*xxx*	Al-Si	Cold work (some heat treat)	105-350	15-50
5*xxx*	Al-Mg (1-2.5% Mg)	Cold work	140-280	20-40

5*xxx*	Al-Mg-Mn (3-6% Mg)	Cold work	280-380	40-55
6*xxx*	Al-Mg-Si	Heat treat	150-380	22-55
7*xxx*	Al-Zn-Mg	Heat treat	380-520	55-75
7*xxx*	Al-Zn-Mg-Cu	Heat treat	520-620	75-90
8*xxx*	Al-Li-Cu-Mg	Heat treat	280-560	40-80

Casting compositions are described by a three-digit system followed by a decimal value. The decimal .0 in all cases pertains to casting alloy limits. Decimals .1, and .2 concern ingot compositions, which after melting and processing should result in chemistries conforming to casting specification requirements. Alloy families for casting compositions include the following:

- 1*xx.x*: Controlled unalloyed (pure) compositions, especially for rotor manufacture
- 2*xx.x*: Alloys in which copper is the principal alloying element. Other alloying elements may be specified.
- 3*xx.x*: Alloys in which silicon is the principal alloying element. The other alloying elements such as copper and magnesium are specified. The 3*xx.x* series comprises nearly 90% of all shaped castings produced.
- 4*xx.x*: Alloys in which silicon is the principal alloying element.
- 5*xx.x*: Alloys in which magnesium is the principal alloying element.
- 6*xx.x*: Unused
- 7*xx.x*: Alloys in which zinc is the principal alloying element. Other alloying elements such as copper and magnesium may be specified.
- 8*xx.x*: Alloys in which tin is the principal alloying element.
- 9*xx.x*: Unused

Heat-treatable casting alloys include the 2*xx*, 3*xx*, and 7*xx* series.

Manufactured Forms

Commercial wrought aluminum products are divided into five major categories based on production method as well as geometric configuration. These categories are (a) flat rolled products (sheet, plate and foil); (b) rod, bar and wire; (c) tubular products; (d) shapes; and (e) forgings. In the aluminum industry, rod, bar, wire, and tubular products and shapes are termed "mill" products, as they are in the steel industry, even though they often are produced by extrusion rather than by rolling. Aluminum forgings usually are not classified as "mill products" but as "engineered products." Engineered products are those designed for one specific application in contrast to "off-the-shelf" products such as standard sizes of sheet, plate, rod, bar, wire, tube, pipe, and standard structural shapes. These standard items may be available from distributors. Engineered wrought products include special extruded shapes, die forgings, hand forgings, impacts, and special sizes of standard products. More detailed information on aluminum mill and engineered wrought products can be found in the article "Aluminum Wrought Products" in this Section.

Aluminum alloy engineered castings, designed for specific purposes, are produced in a great variety of shapes and sizes by pressure-die, permanent-mold, green- and dry-sand, investment, and plaster casting. Process variations include vacuum, low-pressure, centrifugal, and pattern-related processes such as lost foam (each of the aforementioned foundry methods are described in the Section "Casting" in this Handbook). Table 3 provides shipment statistics for aluminum castings. Transportation is the leading market, and the trend toward increasing use in automotive applications is increasing the importance of castings in the total industry picture.

Table 3 Shipments of aluminum castings by type in 1996

Type of casting	Shipments[(a)], 10^6 kg (10^6 lb)	Percentage of total
Die castings	1076.1 (2372.3)	57.7
Permanent mold and semipermanent mold castings	548.4 (1209.1)	29.4
Sand castings	153.9 (339.4)	8.2
Others	87.9 (193.9)	4.7
Total	**1866.4 (4114.6)**	**100**

Source: The Aluminum Association Inc.

(a) Rounded values may not add up to the totals shown.

Die castings generally are not heat treated. Those produced by the other processes may or may not be heat treated, depending on their intended applications, and alloy selection is affected by both the casting process and whether or not heat treatment is to be applied. The most popular alloys differ from those used in producing wrought products chiefly in their higher silicon contents.

The choice of castings over other product forms is often based on net shape considerations. Reinforcing ribs, internal passageways, and complex design features, which would be costly to machine in a part made from a wrought product, can often be cast by appropriate pattern and mold or die design. Premium engineered castings display extreme integrity, close dimensional tolerances, and consistently controlled mechanical properties in the upper range of existing high-strength capabilities for selected alloys and tempers. More detailed information on aluminum castings is included in the article "Aluminum Foundry Products" in this Section.

Powder metallurgy (P/M) parts are formed by various processes. For less demanding applications, metal powder is compressed in a shaped die to produce green compacts, and then the compacts are sintered (diffusion bonded) at elevated temperature under protective atmosphere. During sintering, the compacts consolidate and strengthen. The density of sintered compacts may be increased by re-pressing the P/M compact. Re-pressing may be followed by resintering, which relieves stresses induced by cold work and may further consolidate the structure. By pressing and sintering only, parts having densities of greater than 80% theoretical density can be produced. By re-pressing, with or without resintering, parts of 90% theoretical density or more can be produced.

For more demanding applications, such as aerospace parts or components requiring enhanced resistance to stress-corrosion cracking, rapidly solidified or mechanically attrited aluminum powders are consolidated by more advanced techniques that result in close to 100% of theoretical density. These consolidation methods include hot isostatic pressing, forging, rolling, extrusion, ultra-high strain rate (dynamic) compaction, and spray deposition techniques. Using advanced P/M processing methods, alloys that cannot be produced through conventional ingot metallurgy methods are routinely manufactured. More detailed information on aluminum P/M processing is included in the article "Aluminum Powder Metallurgy Products" in this Section.

Metal-matrix composites (MMCs) basically consist of a nonmetallic reinforcement incorporated into a metallic matrix. The combination of light weight, corrosion resistance, and useful mechanical properties, which has made aluminum alloys so popular, lends itself well to aluminum MMCs. The melting point of aluminum is high enough to satisfy many application requirements, yet is low enough to render composite processing reasonably convenient. Aluminum can also accommodate a variety of reinforcing agents. Reinforcements, characterized as either continuous or discontinuous fibers, typically constitute 20 vol% or more of the composite. The family of aluminum MMC reinforcements includes continuous boron; aluminum oxide; silicon carbide and graphite fibers; and various particles, short fibers, and whiskers. The processing and properties of MMCs are described in the Section "Special-Purpose Materials" in this Handbook.

Fabrication Characteristics

This section briefly reviews importance considerations in the machining, forming, forging, and joining of aluminum alloys. Additional information is included in the Sections in this Handbook that deal with specific fabrication processes. Table 4 summarizes the fabrication characteristics of commonly used wrought grades or alloys.

Table 4 Comparative fabrication characteristics of wrought aluminum alloys

Alloy	Temper	Workability (cold)[(a)]	Machinability[(a)]	Weldability[(b)]			Brazeability[(b)]	Solderability[(c)]
				Gas	**Arc**	**Resistance spot and seam**		
1050	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	A	D	A	A	A	A	A
	H16	B	D	A	A	A	A	A
	H18	B	D	A	A	A	A	A
1060	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	A	D	A	A	A	A	A
	H16	B	D	A	A	A	A	A
	H18	B	D	A	A	A	A	A
1100	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	A	D	A	A	A	A	A

	H16	B	D	A	A	A	A	A
	H18	C	D	A	A	A	A	A
1145	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	A	D	A	A	A	A	A
	H16	B	D	A	A	A	A	A
	H18	B	D	A	A	A	A	A
1199	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A
	H14	A	D	A	A	A	A	A
	H16	B	D	A	A	A	A	A
	H18	B	D	A	A	A	A	A
1350	O	A	E	A	A	B	A	A
	H12, H111	A	E	A	A	A	A	A
	H14, H24	A	D	A	A	A	A	A
	H16, H26	B	D	A	A	A	A	A
	H18	B	D	A	A	A	A	A
2011	T3	C	A	D	D	D	D	C
	T4, T451	B	A	D	D	D	D	C
	T8	D	A	D	D	D	D	C
2014	O	. . .	D	D	D	B	D	C

	T3, T4, T451	C	B	D	B	B	D	C
	T6, T651, T6510, T6511	D	B	D	B	B	D	C
2024	O	. . .	D	D	D	D	D	C
	T4, T3, T351, T3510, T3511	C	B	C	B	B	D	C
	T361	D	B	D	C	B	D	C
	T6	C	B	D	C	B	D	C
	T861, T81, T851, T8510, T8511	D	B	D	C	B	D	C
	T72	. . .	B	. . .	. . .	. . .	. . .	. . .
2036	T4	B	C	. . .	B	B	D	. . .
2124	T851	D	B	D	C	B	D	C
2218	T61	. . .	. . .	. . .	. . .	C	. . .	C
	T72	. . .	B	D	C	B	D	C
2219	O	. . .	. . .	D	A	B	D	. . .
	T31, T351, T3510, T3511	C	B	A	A	A	D	N/A
	T37	D	B	A	A	A	D	. . .
	T81, T851, T8510, T8511	D	B	A	A	A	D	. . .
	T87	D	B	A	A	A	D	. . .
2618	T61	. . .	B	D	C	B	D	NA
3003	O	A	E	A	A	B	A	A
	H12	A	E	A	A	A	A	A

	H14	B	D	A	A	A	A	A
	H16	C	D	A	A	A	A	A
	H18	C	D	A	A	A	A	A
	H25	B	D	A	A	A	A	A
3004	O	A	D	B	A	B	B	B
	H32	B	D	B	A	A	B	B
	H34	B	C	B	A	A	B	B
	H36	C	C	B	A	A	B	B
	H38	C	C	B	A	A	B	B
3105	O	A	E	B	A	B	B	B
	H12	B	E	B	A	B	B	B
	H14	B	D	B	A	A	B	B
	H16	C	D	B	A	A	B	B
	H18	C	D	B	A	A	B	B
	H25	B	D	B	A	A	B	B
4032	T6	. . .	B	D	B	C	D	NA
4043		NA	C	NA	NA	NA	NA	NA
5005	O	A	E	A	A	B	B	B
	H12	A	E	A	A	A	B	B
	H14	B	D	A	A	A	B	B
	H16	C	D	A	A	A	B	B

	H18	C	D	A	A	A	B	B
	H32	B	E	A	A	A	B	B
	H34	C	D	A	A	A	B	B
	H36	C	D	A	A	A	B	B
	H38	. . .	D	A	A	A	B	B
5050	O	A	E	A	A	B	B	C
	H32	A	D	A	A	A	B	C
	H34	B	D	A	A	A	B	C
	H36	C	C	A	A	A	B	C
	H38	C	C	A	A	A	B	C
5052	O	A	D	A	A	B	C	D
	H32	B	D	A	A	A	C	D
	H34	B	C	A	A	A	C	D
	H36	C	C	A	A	A	C	D
	H38	C	C	A	A	A	C	D
5056	O	A	D	C	A	B	D	D
	H111	A	D	C	A	A	D	D
	H12, H32	B	D	C	A	A	D	D
	H14, H34	B	C	C	A	A	D	D
	H18, H38	C	C	C	A	A	D	D
	H192	D	B	C	A	A	D	D

	H392	D	B	C	A	A	D	D
5083	O	B	D	C	A	B	D	D
	H321, H116	C	D	C	A	A	D	D
	H111	C	D	C	A	A	D	D
5086	O	A	D	C	A	B	D	D
	H32, H116	B	D	C	A	A	D	D
	H34	B	C	C	A	A	D	D
	H36	C	C	C	A	A	D	D
	H38	C	C	C	A	A	D	D
	H111	B	D	C	A	A	D	D
5154	O	A	D	C	A	B	D	D
	H32	B	D	C	A	A	D	D
	H34	B	C	C	A	A	D	D
	H36	C	C	C	A	A	D	D
	H38	C	C	C	A	A	D	D
5182	O	A	D	C	A	B	D	D
	H19	D	B	C	A	A	D	D
5252	H24	B	D	A	A	A	C	D
	H25	B	C	A	A	A	C	D
	H28	C	C	A	A	A	C	D
5254	O	A	D	C	A	B	D	D

	H32	B	D	C	A	A	D	D
	H34	B	C	C	A	A	D	D
	H36	C	C	C	A	A	D	D
	H38	C	C	C	A	A	D	D
5356		NA	B	NA	NA	NA	NA	NA
5454	O	A	D	C	A	B	D	. . .
	H32	B	D	C	A	A	D	. . .
	H34	B	C	C	A	A	D	NA
	H111	B	D	C	A	A	D	. . .
5456	O	B	D	C	A	B	D	. . .
	H111	C	D	C	A	A	D	. . .
	H321, H115	C	D	C	A	A	D	NA
5457	O	A	E	A	A	B	B	B
5652	O	A	D	A	A	B	C	D
	H32	B	D	A	A	A	C	D
	H34	B	C	A	A	A	C	D
	H36	C	C	A	A	A	C	D
	H38	C	C	A	A	A	C	D
5657	H241	A	D	A	A	A	B	. . .
	H25	B	D	A	A	A	B	NA
	H26	B	D	A	A	A	B	. . .

	H28	C	D	A	A	A	B	. . .
6005	T5	C	C	A	A	A	A	NA
6009	T4	A	C	A	A	A	A	B
6010	T4	B	C	A	A	A	A	B
6061	O	A	D	A	A	B	A	B
	T4, T451, T4510, T4511	B	C	A	A	A	A	B
	T6, T651, T652, T6510, T6511	C	C	A	A	A	A	B
6063	T1	B	D	A	A	A	A	B
	T4	B	D	A	A	A	A	B
	T5, T52	B	C	A	A	A	A	B
	T6	C	C	A	A	A	A	B
	T83, T831, T832	C	C	A	A	A	A	B
6066	O	B	D	D	B	B	D	. . .
	T4, T4510, T4511	C	C	D	B	B	D	NA
	T6, T6510, T6511	C	B	D	B	B	D	. . .
6070	T4, T4511	B	C	A	A	A	B	NA
	T6	C	C	A	A	A	B	. . .
6101	T6, T63	C	C	A	A	A	A	NA
	T61, T64	B	D	A	A	A	A	. . .
6151	T6, T652	. . .	. . .	. . .	. . .	. . .	. . .	B

6201	T81	. . .	C	A	A	A	A	NA
6262	T6, T651, T6510, T6511	C	B	A	A	A	A	NA
	T9	D	B	A	A	A	A	. . .
6351	T5, T6	C	C	A	A	A	A	B
6463	T1	B	D	A	A	A	A	. . .
	T5	B	C	A	A	A	A	NA
	T6	C	C	A	A	A	A	. . .
7005	T53	C	A	B	B	B	B	B
7049	T73, T7351, T7352	D	B	D	C	B	D	D
	T76, T7651	D	B	D	C	B	D	D
7050	T74, T7451, T7452	D	B	D	C	B	D	D
	T76, T761	D	B	D	C	B	D	D
7072	. . .	A	D	A	A	A	A	A
7075	O	. . .	D	D	C	B	D	D
	T6, T651, T652, T6510, T6511	D	B	D	C	B	D	D
	T73, T7351	D	B	D	C	B	D	D
7175	T74, T7452	D	B	D	C	B	D	D
7178	O	. . .	. . .	D	C	B	D	D
	T6, T651, T6510, T6511	D	B	D	C	B	D	D
7475	T6, T651	D	B	D	C	B	D	D

	T73, T7351, T7352	D	B	D	C	B	D	D
	T76, T7651	D	B	D	C	B	D	D

(a) Ratings A through D for workability (cold), and A through E for machinability, are relative ratings in decreasing order of merit.

(b) Ratings A through D for weldability and brazeability are relative ratings defined as follows: A = Generally weldable by all commercial procedures and methods. B = Weldable with special techniques or for specific applications; requires preliminary trials or testing to develop welding procedure and weld performance. C = Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties. D = No commonly used welding methods have been developed.

(c) Ratings A through D and NA for solderability are relative ratings defined as follows: A = Excellent. B = Good. C = Fair. D = Poor. NA = Not applicable

Machinability. The ease and speed with which aluminum may be machined is one of the most important factors contributing to the low cost of finished aluminum parts. The metal may be turned, milled, bored, or machined in other manners at the maximum speeds of which the majority of machines are capable. Another advantage of its flexible machining characteristics is that aluminum rod and bar may readily be employed in the high speed manufacture of parts by automatic screw machines.

Among the various wrought and cast aluminum alloys and among the tempers in which they are produced, there is considerable variation in machining characteristics (see Table 4), which may require special tooling or techniques (for example, the use of polycrystalline diamond tooling for machining hard (>100 HB) high-silicon-content casting alloys.) Hardness and yield strengths are variously used as approximations of machinability.

Chemical milling, the removal of metal by chemical attack in an alkaline or acid solution, is routine for specialized reductions in thickness. For complex large surface areas in which uniform metal removal is required, chemical milling is often the most economical method. The process is used extensively to etch preformed aerospace parts to obtain maximum strength-to-weight ratios. Integrally stiffened aluminum wing and fuselage sections are chemically milled to produce an optimum cross section and minimum skin thickness. Spars, stringers, floor beams, and frames are frequent applications as well.

Formability is among the more important characteristics of aluminum and many of its alloys. Specific tensile and yield strengths, ductility, and respective rates of work hardening control differences in the amount of permissible deformation.

Ratings of comparable formability of the commercially available alloys in various tempers depend on the forming process. Such ratings provide generally reliable comparisons of the working characteristics of metals, but serve as an approximate guide rather than as quantitative formability limits.

Choice of temper may depend on the severity and nature of forming operations. The annealed temper may be required for severe forming operations, such as deep drawing, or for roll forming or bending on small radii. Usually, the strongest temper than can be formed consistently is selected. For less severe forming operations, intermediate tempers or even fully hardened conditions may be acceptable.

Heat-treatable alloys can be formed in applications for which a high strength-to-weight ratio is required. The annealed temper of these alloys is the most workable condition, but the effects of dimensional change and distortion caused by subsequent heat treatment for property development, and the straightening or other dimensional control steps that may be required, are important considerations. Alloys that are formed immediately following solution heat treatment and quench (T3, T4, or W temper) are nearly as formable as when annealed and can be subsequently hardened by natural or artificial aging. Parts can be stored at low temperatures (approximately -30 to -35 °C, or -20 to -30 °F, or lower) in the W temper for prolonged periods as a means of inhibiting natural aging and preserving an acceptable level of formability. Material that has been solution heat treated and quenched but not artificially aged (T3, T4, or W temper) is generally suitable only for mild forming operations such as bending, mild drawing, or moderate stretch forming if these operations cannot be performed immediately after quenching. Solution heat-treated and artificially aged (T6 temper) alloys are in general unsuitable for forming operations.

Forgeability. Aluminum alloys an be forged into a variety of shapes and types of forgings with a broad range of final part forging design criteria based on the intended application. Aluminum alloy forgings, particularly closed-die forgings, are usually produced to more highly refined final forging configurations than hot-forged carbon and/or alloy steels. For a given aluminum alloy forging shape, the pressure requirements in forging vary widely, depending primarily on the chemical composition of the alloy being forged, the forging process being employed, the forging strain rate, the type of forging being manufactured, the lubrication conditions, and the forging and die temperatures.

As a class of alloys, aluminum alloys are generally considered to be more difficult to forge than carbon steels and many alloy steels. Compared to the nickel/cobalt-base alloys and titanium alloys, however, aluminum alloys are considerably more forgeable, particularly in conventional forging process technology, in which dies are heated to 540 °C (1000 °F) or less.

Joining. Aluminum can be joined by a wide variety of methods, including fusion and resistance welding, brazing, soldering, adhesive bonding, and mechanical methods such as riveting and bolting. Factors that affect the welding of aluminum include:

- Aluminum oxide coating
- Thermal conductivity
- Thermal expansion coefficient
- Melting characteristics
- Electrical conductivity

Aluminum oxide immediately forms on aluminum surfaces exposed to air. Before aluminum can be welded by fusion methods, the oxide layer must be removed mechanically by machining, filing, wire brushing, scraping, or chemical cleaning. If oxides are not removed, oxide fragments may be entrapped in the weld and will cause a reduction in ductility, a lack of fusion, and possibly weld cracking. During welding, the oxide must be prevented from re-forming by shielding the joint area with a nonoxidizing gas such as argon, helium, or hydrogen, or chemically by use of fluxes.

Thermal conductivity is a property that most affects weldability. The thermal conductivity of aluminum alloys is about one-half that of copper and four times that of low-carbon steel. This means that heat must be supplied four times as fast to aluminum alloys as to steel to raise the temperature locally by the same amount. However, the high thermal conductivity of aluminum alloys helps to solidify the molten weld pool of aluminum and, consequently, facilitates out-of-position welding.

The coefficient of linear expansion, which is a measure of the change in length of a material with a change in its temperature, is another physical property of importance when considering weldability. The coefficient of linear thermal expansion for aluminum is twice that for steel. This means that extra care must be taken in welding aluminum to ensure that the joint space remains uniform. This may necessitate preliminary joining of the parts of the assembly by tack welding prior to the main welding operation.

The combination of high coefficient of thermal expansion and high thermal conductivity would cause considerable distortion of aluminum during welding were it not for the high welding speed possible.

Melt Characteristics. The melting ranges for aluminum alloys are considerably lower than those for copper or steel. Melting temperatures and the volumetric specific heats and heats of fusion of aluminum alloys determine that the amount of heat required to enter the welding temperature range is much lower for aluminum alloys.

Electrical conductivity has little influence on fusion welding but is a very important property for materials that are to be resistance welded. In resistance welding, resistance of the metal to the flow of welding current produces heat, which causes the portion of the metal through which the current flows to approach or reach its melting point. Aluminum has higher conductivity than steel, which means that much higher currents are required to produce the same heating effect. Consequently, resistance welding machines for aluminum must have much higher output capabilities than those normally used for steel, for welding comparable sections. Table 4 lists welding, brazing, and soldering characteristics of selected wrought aluminum alloys.

Finishes

The natural metallic surface of aluminum is aesthetically pleasing in many product designs even without further finishing. Its natural protective oxide film is transparent and can be thickened by anodizing, for extra protection, without affecting the metal's appearance.

But aluminum also accepts a great variety of finishes that can alter its appearance or enhance its surface characteristics as required. Surface textures can be created from rough to matte to mirror-smooth. The metallic hue can be colored by appropriate chemical or anodizing processes. Surface coatings such as paint, lacquer, enamel, electroplating or laminates can be applied.

Applications

Aluminum alloys are economical in many applications. They are used in the automotive industry, aerospace industry, in construction of machines, appliances, and structures, as cooking utensils, as covers for housings for electronic equipment, as pressure vessels for cryogenic applications, and in innumerable other areas. Tables 5 and 6 list typical applications for some of the more commonly used wrought and cast alloys, respectively.

Table 5 Selected applications for wrought aluminum alloys

Alloy	Description and selected applications
1100	Commercially pure aluminum highly resistant to chemical attack and weathering. Low cost, ductile for deep drawing, and easy to weld. Used for high-purity applications such as chemical processing equipment. Also for nameplates, fan blades, flue lining, sheet metal work, spun holloware, and fin stock
1350	Electrical conductors
2011	Screw machine products. Appliance parts and trim, ordnance, automotive, electronic, fasteners, hardware, machine parts
2014	Truck frames, aircraft structures, automotive, cylinders and pistons, machine parts, structurals
2017	Screw machine products, fittings, fasteners, machine parts
2024	For high-strength structural applications. Excellent machinability in the T-tempers. Fair workability and fair corrosion resistance. Alclad 2024 combines the high strength of 2024 with the corrosion resistance of the commercially pure cladding. Used for truck wheels, many structural aircraft applications, gears for machinery, screw machine products, automotive parts, cylinders and pistons, fasteners, machine parts, ordnance, recreation equipment, screws and rivets
2219	Structural uses at high temperature (to 315 °C, or 600 °F). High-strength weldments
3003	Most popular general-purpose alloy. Stronger than 1100 with same good formability and weldability. For general use including sheet metal work, stampings, fuel tanks, chemical equipment, containers, cabinets, freezer liners, cooking utensils, pressure vessels, builder's hardware, storage tanks, agricultural applications, appliance parts and trim, architectural applications, electronics, fin stock, fan equipment, name plates, recreation vehicles, trucks and trailers. Used in drawing and spinning.
3004	Sheet metal work, storage tanks, agricultural applications, building products, containers, electronics, furniture, kitchen equipment, recreation vehicles, trucks and trailers

3105	Residential siding, mobile homes, rain-carrying goods, sheet metal work, appliance parts and trim, automotive parts, building products, electronics, fin stock, furniture, hospital and medical equipment, kitchen equipment, recreation vehicles, trucks and trailers
5005	Specified for applications requiring anodizing; anodized coating is cleaner and lighter in color than 3003. Uses include appliances, utensils, architectural, applications requiring good electrical conductivity, automotive parts, containers, general sheet metal, hardware, hospital and medical equipment, kitchen equipment, name plates, and marine applications
5052	Stronger than 3003 yet readily formable in the intermediate tempers. Good weldability and resistance to corrosion. Uses include pressure vessels, fan blades, tanks, electronic panels, electronic chassis, medium-strength sheet metal parts, hydraulic tube, appliances, agricultural applications, architectural uses, automotive parts, building products, chemical equipment, containers, cooking utensils, fasteners, hardware, highway signs, hospital and medical equipment, kitchen equipment, marine applications, railroad cars, recreation vehicles, trucks and trailers
5056	Cable sheathing, rivets for magnesium, screen wire, zippers, automotive applications, fence wire, fasteners
5083	For all types of welded assemblies, marine components, and tanks requiring high weld efficiency and maximum joint strength. Used in pressure vessels up to 65 °C (150 °F) and in many cryogenic applications, bridges, freight cars, marine components, TV towers, drilling rigs, transportation equipment, missile components, and dump truck bodies. Good corrosion resistance
5086	Used in generally the same types of applications as 5083, particularly where resistance to either stress corrosion or atmospheric corrosion is important
5454	For all types of welded assemblies, tanks, pressure vessels. ASME code approved to 205 °C (400 °F). Also used in trucking for hot asphalt road tankers and dump bodies; also, for hydrogen peroxide and chemical storage vessels
5456	For all types of welded assemblies, storage tanks, pressure vessels, and marine components. Used where best weld efficiency and joint strength are required. Restricted to temperatures below 65 °C (150 °F)
5657	For anodized auto and appliance trim and nameplates
6061	Good formability, weldability, corrosion resistance, and strength in the T-tempers. Good general-purpose alloy used for a broad range of structural applications and welded assemblies including truck components, railroad cars, pipelines, marine applications, furniture, agricultural applications, aircrafts, architectural applications, automotive parts, building products, chemical equipment, dump bodies, electrical and electronic applications, fasteners, fence wire, fan blades, general sheet metal, highway signs, hospital and medical equipment, kitchen equipment, machine parts, ordnance, recreation equipment, recreation vehicles, and storage tanks
6063	Used in pipe railing, furniture, architectural extrusions, appliance parts and trim, automotive parts, building products, electrical and electronic parts, highway signs, hospital and medical equipment, kitchen equipment, marine applications, machine parts, pipe, railroad cars, recreation equipment, recreation vehicles, trucks and trailers
7050	High-strength alloy in aircraft and other structures. Also used in ordnance and recreation equipment
7075	For aircraft and other applications requiring highest strengths. Alclad 7075 combines the strength advantages of 7075 with the corrosion-resisting properties of commercially pure aluminum-clad surface. Also used in machine parts and ordnance

Table 6 Selected applications for aluminum casting alloys

Alloy	Representative applications

100.0	Electrical rotors larger than 152 mm (6 in.) in diameter
201.0	Structural members; cylinder heads and pistons; gear, pump, and aerospace housings
208.0	General-purpose castings; valve bodies, manifolds, and other pressure-tight parts
222.0	Bushings; meter parts; bearings; bearing caps; automotive pistons; cylinder heads
238.0	Sole plates for electric hand irons
242.0	Heavy-duty pistons; air-cooled cylinder heads; aircraft generator housings
A242.0	Diesel and aircraft pistons; air-cooled cylinder heads; aircraft generator housings
B295.0	Gear housings; aircraft fittings; compressor connecting rods; railway car seat frames
308.0	General-purpose permanent mold castings; ornamental grilles and reflectors
319.0	Engine crankcases; gasoline and oil tanks; oil pans; typewriter frames; engine parts
332.0	Automotive and heavy-duty pistons; pulleys, sheaves
333.0	Gas meter and regulator parts; gear blocks; pistons; general automotive castings
354.0	Premium-strength castings for the aerospace industry
355.0	Sand: air compressor pistons; printing press bedplates; water jackets; crankcases. Permanent: impellers; aircraft fittings; timing gears; jet engine compressor cases
356.0	Sand: flywheel castings; automotive transmission cases; oil pans; pump bodies. Permanent: machine tool parts; aircraft wheels; airframe castings; bridge railings
A356.0	Structural parts requiring high strength; machine parts; truck chassis parts
357.0	Corrosion-resistant and pressure-tight applications
359.0	High-strength castings for the aerospace industry
360.0	Outboard motor parts; instrument cases; cover plates; marine and aircraft castings
A360.0	Cover plates; instrument cases; irrigation system parts; outboard motor parts; hinges

380.0	Housings for lawn mowers and radio transmitters; air brake castings; gear cases
A380.0	Applications requiring strength at elevated temperature
384.0	Pistons and other severe service applications; automatic transmissions
390.0	Internal combustion engine pistons, blocks, manifolds, and cylinder heads
413.0	Architectural, ornamental, marine, and food and dairy equipment applications
A413.0	Outboard motor pistons; dental equipment; typewriter frames; street lamp housings
443.0	Cookware; pipe fittings; marine fittings; tire molds; carburetor bodies
514.0	Fittings for chemical and sewage use; dairy and food handling equipment; tire molds
A514.0	Permanent mold casting of architectural fittings and ornamental hardware
518.0	Architectural and ornamental castings; conveyor parts; aircraft and marine castings
520.0	Aircraft fittings; railway passenger care frames; truck and bus frame sections
535.0	Instrument parts and other applications where dimensional stability is important
A712.0	General-purpose castings that require subsequent brazing
713.0	Automotive parts; pumps; trailer parts; mining equipment
850.0	Bushings and journal bearings for railroads
A850.0	Rolling mill bearings and similar applications

Alloy and Temper Designation Systems for Aluminum

Introduction

SYSTEMS FOR DESIGNATING aluminum and aluminum alloys that incorporate the product form (wrought, casting, or foundry ingot), and its respective temper (with the exception of foundry ingots, which have no temper classification) are covered by American National Standards Institute (ANSI) standard H35.1. The Aluminum Association is the registrar under ANSI H35.1 with respect to the designation and composition of aluminum alloys and tempers registered in the United States.

Wrought Aluminum and Aluminum Alloy Designation System

A four-digit numerical designation system is used to identify wrought aluminum and aluminum alloys. As shown below, the first digit of the four-digit designation indicates the group:

Aluminum, ≥99.00%	**1*xxx***
Aluminum alloys grouped by major alloying element(s):	
Copper	2*xxx*
Manganese	3*xxx*
Silicon	4*xxx*
Magnesium	5*xxx*
Magnesium and silicon	6*xxx*
Zinc	7*xxx*
Other elements	8*xxx*
Unused series	9*xxx*

For the 2*xxx* through 7*xxx* series, the alloy group is determined by the alloying element present in the greatest mean percentage. An exception is the 6*xxx* series alloys in which the proportions of magnesium and silicon available to form magnesium silicide (Mg_2Si) are predominant. Another exception is made in those cases in which the alloy qualifies as a modification of a previously registered alloy. If the greatest mean percentage is the same for more than one element, the choice of group is in order of group sequence: copper, manganese, silicon, magnesium, magnesium silicide, zinc, or others.

Aluminum. In the 1*xxx* group, the series 10*xx* is used to designate unalloyed compositions that have natural impurity limits. The last two of the four digits in the designation indicate the minimum aluminum percentage. These digits are the same as the two digits to the right of the decimal point in the minimum aluminum percentage when expressed to the nearest 0.01%. Designations having second digits other than zero (integers 1 through 9, assigned consecutively as needed) indicate special control of one or more individual impurities.

Aluminum Alloys. In the 2*xxx* through 8*xxx* alloy groups, the second digit in the designation indicates alloy modification. If the second digit is zero, it indicates the original alloy; integers 1 through 9, assigned consecutively, indicate modifications of the original alloy. Explicit rules have been established for determining whether a proposed composition is merely a modification of a previously registered alloy or if it is an entirely new alloy. The last two of the four digits in the 2*xxx* through 8*xxx* groups have no special significance, but serve only to identify the different aluminum alloys in the group.

Cast Aluminum and Aluminum Alloy Designation System

A system of four-digit numerical designations incorporating a decimal point is used to identify aluminum and aluminum alloys in the form of castings and foundry ingot. The first digit indicates the alloy group:

Aluminum, ≥99.00%	1*xx.x*
Aluminum alloys grouped by major alloying element(s):	
Copper	2*xx.x*
Silicon, with added copper and/or magnesium	3*xx.x*
Silicon	4*xx.x*
Magnesium	5*xx.x*
Zinc	7*xx.x*
Tin	8*xx.x*
Other elements	9*xx.x*
Unused series	6*xx.x*

For 2*xx.x* through 9*xx.x* (excluding 6*xx.x* alloys), the alloy group is determined by the alloying element present in the greatest mean percentage, except in cases in which the composition being registered qualifies as a modification of a previously registered alloy. If the greatest mean percentage is common to more than one alloying element, the alloy group is determined by the element that comes first in the sequence.

The second two digits identify the specific aluminum alloy or, for the aluminum (1*xx.x*) series, indicate purity. The last digit, which is separated from the others by a decimal point, indicates the product form, whether casting or ingot. A modification of an original alloy, or of the impurity limits for unalloyed aluminum, is indicated by a serial letter preceding the numerical designation. The serial letters are assigned in alphabetical sequence starting with A but omitting I, O, Q, and X, the X being reserved for experimental alloys. Explicit rules have been established for determining whether a proposed composition is a modification of an existing alloy or if it is a new alloy.

Aluminum Castings and Ingot. For the 1*xx.x* group, the second two of the four digits in the designation indicate the minimum aluminum percentage. These digits are the same as the two digits to the right of the decimal point in the minimum aluminum percentage when expressed to the nearest 0.01%. The last digit indicates the product form: 1*xx*.0 indicates castings, and 1*xx*.1 indicates ingot.

Aluminum Alloy Castings and Ingot. For the 2*xx.x* through 9*xx.x* alloy groups, the second two of the four digits in the designation have no special significance but serve only to identify the different alloys in the group. The last digit, which is to the right of the decimal point, indicates the produce form: *xxx*.0 indicates castings, and *xxx*.1 indicates ingot having limits for alloying elements the same as those for the alloy in the form of castings, except for those listed in Table 1.

Table 1 Alloying element and impurity specifications for ingots that will be remelted into sand, permanent mold, and die castings

Alloying element	Composition, wt%			
	Casting			**Ingot**
	Sand and permanent mold	**Die**	**All**	
Iron	$\leq$0.15	. . .	. . .	Casting -0.03
	>0.15-0.25	. . .	. . .	Casting -0.05
	>0.25-0.6	. . .	. . .	Casting -0.10
	>0.6-1.0	. . .	. . .	Casting -0.2
	>1.0	. . .	. . .	Casting -0.3
	. . .	$\leq$1.3	. . .	Casting -0.3
	. . .	>1.3	. . .	$\leq$1.1
Magnesium	. . .	. . .	<0.50	Casting +0.05[(a)]
	. . .	. . .	$\geq$0.50	Casting +0.1[(a)]
Zinc	. . .	>0.25-0.60	. . .	Casting -0.10

	. . .	>0.60	. . .	Casting -0.1

Source: ANSI H35.1-1997

(a) Applicable only when the specified range for castings is >0.15% Mg.

Designations for Experimental Alloys

Experimental alloys also are designated in accordance with the systems for wrought and cast alloys, but they are indicated by the prefix X. The prefix is dropped when the alloy is no longer experimental. During development and before they are designated as experimental, new alloys may be identified by serial numbers assigned by their originators. Use of the serial number is discontinued when the ANSI H35.1 designation is assigned.

Temper Designation System for Aluminum and Aluminum Alloys

The temper designation system used in the United States for aluminum and aluminum alloys is used for all product forms (both wrought and cast), with the exception of ingot. The system is based on the sequences of mechanical or thermal treatments, or both, used to produce the various tempers. The temper designation follows the alloy designation and is separated from it by a hyphen. Basic temper designations consist of individual capital letters. Major subdivisions of basic tempers, where required, are indicated by one or more digits following the letter. These digits designate specific sequences of treatments that produce specific combinations of characteristics in the product. Variations in treatment conditions within major subdivisions are identified by additional digits. The conditions during heat treatment (such as time, temperature, and quenching rate) used to produce a given temper in one alloy may differ from those employed to produce the same temper in another alloy.

Basic Temper Designations

F, As-Fabricated. This is applied to products shaped by cold working, hot working, or casting processes in which no special control over thermal conditions or strain hardening is employed. For wrought products, there are no mechanical property limits.

O, Annealed. O applies to wrought products that are annealed to obtain lowest-strength temper and to cast products that are annealed to improve ductility and dimensional stability. The O may be followed by a digit other than zero.

H, Strain-Hardened (Wrought Products Only). This indicates products that have been strengthened by strain hardening, with or without supplementary thermal treatment to produce some reduction in strength. The H is always followed by two or more digits, as discussed in the section "System for Strain-Hardened Products" in this article.

W, Solution Heat-Treated. This is an unstable temper applicable only to alloys whose strength naturally (spontaneously) changes at room temperature over a duration of months or even years after solution heat treatment. The designation is specific only when the period of natural aging is indicated (for example, W $\frac{1}{2}$ h). See also the discussion of the T*x*51, T*x*52, and T*x*54 tempers in the section "System for Heat-Treatable Alloys" in this article.

T, Solution Heat-Treated. This applies to alloys whose strength is stable within a few weeks of solution heat treatment. The T is always followed by one or more digits, as discussed in the section "System for Heat-Treatable Alloys" in this article.

System for Strain-Hardened Products

Temper designations for wrought products that are strengthened by strain hardening consist of an H followed by two or more digits. The first digit following the H indicates the specific sequence of basic operations.

H1, Strain-Hardened Only. This applies to products that are strain hardened to obtain the desired strength without supplementary thermal treatment. The digit following the H1 indicates the degree of strain hardening.

H2, Strain-Hardened and Partially Annealed. This pertains to products that are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. For alloys that age soften at room temperature, each H2*x* temper has the same minimum ultimate tensile strength as the H3*x* temper with the same second digit. For other alloys, each H2*x* temper has the same minimum ultimate tensile strength as the H1*x* with the same second digit, and slightly higher elongation. The digit following the H2 indicates the degree of strain hardening remaining after the product has been partially annealed.

H3, Strain-Hardened and Stabilized. This applies to products that are strain-hardened and whose mechanical properties are stabilized by a low-temperature thermal treatment or as a result of heat introduced during fabrication. Stabilization usually improves ductility. This designation applies only to those alloys that, unless stabilized, gradually age soften at room temperature. The digit following the H3 indicates the degree of strain hardening remaining after stabilization.

H4, Strain-Hardened and Lacquered or Painted. This applies to products that are strain-hardened and that are also subjected to some thermal operation during subsequent painting or lacquering. The number following this designation indicates the degree of strain-hardening remaining after the product has been thermally treated as part of the painting/lacquering cure operation. The corresponding H2*x* or H3*x* mechanical property limits apply.

Additional Temper Designations. The digit following the designation H1, H2, H3, and H4 indicates the degree of strain-hardening as identified by the *minimum* value of the ultimate tensile strength. The numeral 8 has been assigned to the hardest tempers normally produced. The minimum tensile strength of tempers H*x*8 can be determined from Table 2 and is based on the minimum tensile strength of the alloy (given in ksi units) in the annealed temper. However, temper registrations prior to 1992 that do not conform to the requirements of Table 2 shall not be revised and registrations of intermediate or modified tempers for such alloy/temper systems shall conform to the registration requirements that existed prior to 1992.

Table 2 Minimum tensile requirements for the H*x*8 tempers

Minimum tensile strength in annealed temper, ksi	Increase in tensile strength to H*x*8 temper, ksi
≤6	8
7-9	9
10-12	10
13-15	11
16-18	12
19-24	13
25-30	14
31-36	15

37-42	16
≥43	17

Source: ANSI H35.1-1997

Tempers between O (annealed) and H*x*8 are designated by numerals 1 through 7 as follows:

- Numeral 4 designates tempers whose ultimate tensile strength is approximately midway between that of the O temper and that of the H*x*8 tempers.
- Numeral 2 designates tempers whose ultimate tensile strength is approximately midway between that of the O temper and that of the H*x*4 tempers.
- Numeral 6 designates tempers whose ultimate tensile strength is approximately midway between that of the H*x*4 tempers and that of the H*x*8 tempers.
- Numerals 1, 3, 5, and 7 designate, similarly, tempers intermediate between those defined above.
- Numeral 9 designates tempers whose minimum ultimate tensile strength exceeds that of the H*x*8 tempers by 2 ksi or more.

The ultimate tensile strength of intermediate tempers, determined as described above, when not ending in 0 or 5, shall be rounded to the next higher 0 or 5.

When it is desirable to identify a variation of a two-digit H temper, a third digit (from 1 to 9) may be assigned. The third digit is used when the degree of control of temper or the mechanical properties are different from but close to those for the two-digit H temper designation to which it is added, or when some other characteristic is significantly affected. The minimum ultimate tensile strength of a three-digit H temper is at least as close to that of the corresponding two-digit H temper as it is to either of the adjacent two-digit H tempers. Products in H tempers whose mechanical properties are below those of H*x*1 tempers are assigned variations of H*x*1. Some three-digit H temper designations have already been assigned for wrought products in all alloys:

- H*x*11 applies to products that incur sufficient strain hardening after final annealing to fail to qualify as 0 temper, but not so much or so consistent an amount of strain hardening to qualify as H*x*1 temper.
- H112 pertains to products that may acquire some strain hardening during working at elevated temperature and for which there are mechanical property limits.
- H temper designations assigned to patterned or embossed sheet are listed in Table 3.

Table 3 H temper designations for aluminum and aluminum alloy patterned or embossed sheet

Patterned or embossed sheet	Temper of sheet from which textured sheet was fabricated
H114	O
H124	H11
H224	H21
H324	H31

H134	H12
H234	H22
H334	H32
H144	H13
H244	H23
H344	H33
H154	H14
H254	H24
H354	H34
H164	H15
H264	H25
H364	H35
H174	H16
H274	H26
H374	H36
H184	H17
H284	H27
H384	H37
H194	H18
H294	H28
H394	H38

H195	H19
H295	H29
H395	H39

Source: ANSI H35.1-1997

System for Heat-Treatable Alloys

The temper designation system for wrought and cast products that are strengthened by heat treatment employs the W and T designations described in the section "Basic Temper Designations" in this article. The W designation denotes an unstable temper, whereas the T designation denotes a stable temper other than F, O, or H. The T is followed by a number from 1 to 10, each number indicating a specific sequence of basic treatments.

T1, Cooled from an Elevated-Temperature Shaping Process and Naturally Aged to a Substantially Stable Condition. This designation applies to products that are not cold worked after an elevated-temperature shaping process such as casting or extrusion and for which mechanical properties have been stabilized by room-temperature aging. It also applies to products that are flattened or straightened after cooling from the shaping process, for which the effects of the cold work imparted by flattening or straightening are not accounted for in specified property limits.

T2, Cooled from an Elevated-Temperature Shaping Process, Cold Worked, and Naturally Aged to a Substantially Stable Condition. This variation refers to products that are cold worked specifically to improve strength after cooling from a hot-working process such as rolling or extrusion and for which mechanical properties have been stabilized by room-temperature aging. It also applies to products in which the effects of cold work, imparted by flattening or straightening, are accounted for in specified property limits.

T3, Solution Heat Treated, Cold Worked, and Naturally Aged to a Substantially Stable Condition. T3 applies to products that are cold worked specifically to improve strength after solution heat treatment and for which mechanical properties have been stabilized by room-temperature aging. It also applies to products in which the effects of cold work, imparted by flattening or straightening, are accounted for in specified property limits.

T4, Solution Heat Treated and Naturally Aged to a Substantially Stable Condition. This signifies products that are not cold worked after solution heat treatment and for which mechanical properties have been stabilized by room-temperature aging. If the products are flattened or straightened, the effects of the cold work imparted by flattening or straightening are not accounted for in specified property limits.

T5, Cooled from an Elevated-Temperature Shaping Process and Artificially Aged. T5 includes products that are not cold worked after an elevated-temperature shaping process such as casting or extrusion and for which mechanical properties have been substantially improved by precipitation heat treatment. If the products are flattened or straightened after cooling from the shaping process, the effects of the cold work imparted by flattening or straightening are not accounted for in specified property limits.

T6, Solution Heat Treated and Artificially Aged. This group encompasses products that are not cold worked after solution heat treatment and for which mechanical properties or dimensional stability, or both, have been substantially improved by precipitation heat treatment. If the products are flattened or straightened, the effects of the cold work imparted by flattening or straightening are not accounted for in specified property limits.

T7, Solution Heat Treated and Overaged or Stabilized. T7 applies to wrought products that have been precipitation heat treated beyond the point of maximum strength to provide some special characteristic, such as enhanced resistance to stress-corrosion cracking or exfoliation corrosion. It applies to cast products that are artificially aged after solution heat treatment to provide dimensional and strength stability.

T8, Solution Heat Treated, Cold Worked, and Artificially Aged. This designation applies to products that are cold worked specifically to improve strength after solution heat treatment and for which mechanical properties or dimensional stability, or both, have been substantially improved by precipitation heat treatment. The effects of cold work, including any cold work imparted by flattening or straightening, are accounted for in specified property limits.

T9, Solution Heat Treated, Artificially Aged, and Cold Worked. This grouping is comprised of products that are cold worked specifically to improve strength after they have been precipitation heat treated.

T10, Cooled from an Elevated-Temperature Shaping Process, Cold Worked, and Artificially Aged. T10 identifies products that are cold worked specifically to improved strength after cooling from a hot-working process such as rolling or extrusion and for which mechanical properties have been substantially improved by precipitation heat treatment. The effects of cold work, including any cold work imparted by flattening or straightening, are accounted for in specified property limits.

Additional T Temper Variations. When it is desirable to identify a variation of one of the ten major T tempers described above, additional digits, the first of which cannot be zero, may be added to the designation. Specific sets of additional digits have been assigned to the following wrought products that have been stress relieved by stretching, compressing, or a combination of stretching and compressing:

Product form	Permanent set, %
Plate	$1\frac{1}{2}$-3
Rolled or cold-finished rod and bar	1-3
Extruded rod, bar, profiles (shapes), and tube	1-3
Drawn tube	$\frac{1}{2}$-3
Die or ring forgings and rolled rings	1-5

Stress relieved by stretching includes the following.

T*x*51 applies specifically to plate, to rolled or cold-finished road and bar, to die or ring forgings, and to rolled rings when stretched to the indicated amounts after solution heat treatment or after cooling from an elevated-temperature shaping process. These products receive no further straightening after stretching.

T*x*510 applies to extruded rod, bar, shapes and tubing, and to drawn tubing when stretched to the indicated amounts after solution heat treatment or after cooling from an elevated-temperature shaping process. Products in this temper receive no further straightening after stretching.

T*x*511 applies to extruded rod, bar, profiles (shapes) and tube and to drawn tube when stretched to the indicated amounts after solution heat treatment or after cooling from an elevated temperature shaping process. These products may receive minor straightening after stretching to comply with standard tolerances.

Stress relieved by compressing includes the following.

T*x*52 applies to products that are stress relieved by compressing after solution heat treatment or after cooling from a hot-working process to produce a permanent set of 1 to 5%.

Stress relieved by combined stretching and compressing includes the following.

T*x*54 applies to die forgings that are stress relieved by restriking cold in the finish die.

The same digits (51, 52, and 54) can be added to the designation W to indicate unstable solution-heat-treated and stress-relieved tempers.

Temper designations have been assigned to wrought products heat treated from the O or the F temper to demonstrate response to heat treatment.

T42 means solution heat treated from the O or the F temper to demonstrate response to heat treatment and naturally aged to a substantially stable condition.

T62 means solution heat treated from the O or the F temper to demonstrate response to heat treatment and artificially aged.

T7*x*2 means solution heat treated from the O or F temper and artificially overaged to meet the mechanical properties and corrosion resistance limits of the T7*x* temper.

Temper designations T42 and T62 also may be applied to wrought products heat treated from any temper by the user when such heat treatment results in the mechanical properties applicable to these tempers.

System for Annealed Products

A digit following the "O" indicates a product in annealed condition having special characteristics. For example, for heat-treatable alloys, O1 indicates a product that has been heat treated at approximately the same time and temperature required for solution heat treatment and then air cooled to room temperature; this designation applies to products that are to be machined prior to solution heat treatment by the user. Mechanical property limits are not applicable.

Designation of Unregistered Tempers

The letter P has been assigned to denote H, T, and O temper variations that are negotiated between manufacturer and purchaser. The letter P follows the temper designation that most nearly pertains. The use of this type of designation includes the following situations:

- The use of the temper is sufficiently limited to preclude its registration.
- The test conditions are different from those required for registration with the Aluminum Association.
- The mechanical property limits are not established on the same basis as required for registration with the Aluminum Association.
- It is used for products such as aluminum metal-matrix composites, which are not included in any registration records. (A proposed nomenclature system for aluminum metal-matrix composites is described in the Section "Special-Purpose Materials" in this Handbook.)

Chemical Compositions and International Designations for Aluminum Alloys

Introduction

MORE THAN 450 ALLOY designations/compositions have been registered by the Aluminum Association Inc. for aluminum and aluminum alloys. Table 1 lists the designations and composition limits of wrought unalloyed aluminum and wrought aluminum alloys. Table 2 lists designations and composition limits for aluminum alloys in the form of castings and ingot.

Table 1 Composition limits for wrought aluminum and aluminum alloys

AA No.	Composition, wt%														
	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Ni**	**Zn**	**Ga**	**V**	**Specified other elements**	**Ti**	**Unspecified other elements**		**Al, min**
													Each	**Total**	
1035	0.35	0.6	0.10	0.05	0.05	. . .	. . .	0.10	. . .	0.05	. . .	0.03	0.03	. . .	99.35
1040	0.30	0.50	0.10	0.05	0.05	. . .	. . .	0.10	. . .	0.05	. . .	0.03	0.03	. . .	99.40
1045	0.30	0.45	0.10	0.05	0.05	. . .	. . .	0.05	. . .	0.05	. . .	0.03	0.03	. . .	99.45
1050	0.25	0.40	0.05	0.05	0.05	. . .	. . .	0.05	. . .	0.05	. . .	0.03	0.03	. . .	99.50
1060	0.25	0.35	0.05	0.03	0.03	. . .	. . .	0.05	. . .	0.05	. . .	0.03	0.03	. . .	99.60
1065	0.25	0.30	0.05	0.03	0.03	. . .	. . .	0.05	. . .	0.05	. . .	0.03	0.03	. . .	99.65
1070	0.20	0.25	0.04	0.03	0.03	. . .	. . .	0.04	. . .	0.05	. . .	0.03	0.03	. . .	99.70
1080	0.15	0.15	0.03	0.02	0.02	. . .	. . .	0.03	0.03	0.05	. . .	0.03	0.02	. . .	99.80
1085	0.10	0.12	0.03	0.02	0.02	. . .	. . .	0.03	0.03	0.05	. . .	0.02	0.01	. . .	99.85
1090	0.07	0.07	0.02	0.01	0.01	. . .	. . .	0.03	0.03	0.05	. . .	0.01	0.01	. . .	99.90
1100	0.95 Si + Fe		0.05-0.20	0.05	. . .	. . .	. . .	0.10	. . .	. . .	(a)	. . .	0.05	0.15	99.0

1200	1.00 Si + Fe		0.05	0.05	. . .	. . .	. . .	0.10	. . .	. . .	. . .	0.05	0.05	0.15	99.0
1230	0.70 Si + Fe		0.10	0.05	0.05	. . .	. . .	0.10	. . .	0.05	. . .	0.03	0.03	. . .	99.30
1135	0.60 Si + Fe		0.05-0.20	0.04	0.05	. . .	. . .	0.10	. . .	0.05	. . .	0.03	0.03	. . .	99.35
1235	0.65 Si + Fe		0.05	0.05	0.05	. . .	. . .	0.10	. . .	0.05	. . .	0.06	0.03	. . .	99.35
1435	0.15	0.30-0.50	0.02	0.05	0.05	. . .	. . .	0.10	. . .	0.05	. . .	0.03	0.03	. . .	99.35
1145	0.55 Si + Fe		0.05	0.05	0.05	. . .	. . .	0.05	. . .	0.05	. . .	0.03	0.03	. . .	99.45
1345	0.30	0.40	0.10	0.05	0.05	. . .	. . .	0.05	. . .	0.05	. . .	0.03	0.03	. . .	99.45
1350	0.10	0.40	0.05	0.01	. . .	0.01	. . .	0.05	0.03	. . .	0.05 B, 0.02 V + Ti	. . .	0.03	0.10	99.50
1170	0.30 Si + Fe		0.03	0.03	0.02	0.03	. . .	0.04	. . .	0.05	. . .	0.03	0.03	. . .	99.70
1175	0.15 Si + Fe		0.10	0.02	0.02	. . .	. . .	0.04	0.03	0.05	. . .	0.02	0.02	. . .	99.75
1180	0.09	0.09	0.01	0.02	0.02	. . .	. . .	0.03	0.03	0.05	. . .	0.02	0.02	. . .	99.80
1185	0.15 Si + Fe		0.01	0.02	0.02	. . .	. . .	0.03	0.03	0.05	. . .	0.02	0.01	. . .	99.85
1285	0.08(b)	0.08(b)	0.02	0.01	0.01	. . .	. . .	0.03	0.03	0.05	. . .	0.02	0.01	. . .	99.85
1188	0.06	0.06	0.005	0.01	0.01	. . .	. . .	0.03	0.03	0.05	(a)	0.01	0.01	. . .	99.88
1199	0.006	0.006	0.006	0.002	0.006	. . .	. . .	0.006	0.005	0.005	. . .	0.002	0.002	. . .	99.99
2008	0.50-0.8	0.40	0.7-1.1	0.30	0.25-0.50	0.10	. . .	0.25	. . .	0.05	. . .	0.10	0.05	0.15	bal
2009	0.25	0.05	3.2-4.4	. . .	1.0-1.6	. . .	. . .	0.10	. . .	. . .	(c)	. . .	0.05	0.15	bal
2010	0.50	0.50	0.7-1.3	0.10-0.40	0.40-1.0	0.15	. . .	0.30	. . .	. . .	. . .	. . .	0.05	0.15	bal

2011	0.40	0.7	5.0-6.0	. . .	. . .	. . .	. . .	0.30	. . .	. . .	(d)	. . .	0.05	0.15	bal
2111	0.40	0.7	5.0-6.0	. . .	. . .	. . .	. . .	0.30	. . .	. . .	(e)	. . .	0.05	0.15	bal
2012	0.40	0.7	4.0-5.5	. . .	. . .	. . .	. . .	0.30	. . .	. . .	(f)	. . .	0.05	0.15	bal
2014	0.50-1.2	0.7	3.9-5.0	0.40-1.2	0.20-0.8	0.10	. . .	0.25	. . .	. . .	(g)	0.15	0.05	0.15	bal
2214	0.50-1.2	0.30	3.9-5.0	0.40-1.2	0.20-0.8	0.10	. . .	0.25	. . .	. . .	(g)	0.15	0.05	0.15	bal
2017	0.20-0.8	0.7	3.5-4.5	0.40-1.0	0.40-0.8	0.10	. . .	0.25	. . .	. . .	(g)	0.15	0.05	0.15	bal
2117	0.8	0.7	2.2-3.0	0.20	0.20-0.50	0.10	. . .	0.25	. . .	. . .	. . .	. . .	0.05	0.15	bal
2018	0.9	1.0	3.5-4.5	0.20	0.45-0.9	0.10	1.7-2.3	0.25	. . .	. . .	. . .	. . .	0.05	0.15	bal
2218	0.9	1.0	3.5-4.5	0.20	1.2-1.8	0.10	1.7-2.3	0.25	. . .	. . .	. . .	. . .	0.05	0.15	bal
2618	0.10-0.25	0.9-1.3	1.9-2.7	. . .	1.3-1.8	. . .	0.9-1.2	0.10	. . .	. . .	. . .	0.04-0.10	0.05	0.15	bal
2219	0.20	0.30	5.8-6.8	0.20-0.40	0.02	. . .	. . .	0.10	. . .	0.05-0.15	0.10-0.25 Zr	0.02-0.10	0.05	0.15	bal
2319	0.20	0.30	5.8-6.8	0.20-0.40	0.02	. . .	. . .	0.10	. . .	0.05-0.15	0.10-0.25 Zr(a)	0.10-0.20	0.05	0.15	bal
2419	0.15	0.18	5.8-6.8	0.20-0.40	0.02	. . .	. . .	0.10	. . .	0.05-0.15	0.10-0.25 Zr	0.02-0.10	0.05	0.15	bal
2519	0.25(h)	0.30(h)	5.3-6.4	0.10-0.50	0.50-0.40	. . .	. . .	0.10	. . .	0.05-0.15	0.10-0.25 Zr	0.02-0.10	0.05	0.15	bal
2024	0.50	0.50	3.8-4.9	0.30-0.9	1.2-1.8	0.10	. . .	0.25	. . .	·	(g)	0.15	0.05	0.15	bal
2124	0.20	0.30	3.8-4.9	0.30-0.9	1.2-1.8	0.10	. . .	0.25	. . .	. . .	(g)	0.15	0.05	0.15	bal

2224	0.12	0.15	3.8-4.4	0.30-0.9	1.2-1.8	0.10	. . .	0.25	. . .	. . .	. . .	0.15	0.05	0.15	bal
2324	0.10	0.12	3.8-4.4	0.30-0.9	1.2-1.8	0.10	. . .	0.25	. . .	. . .	. . .	0.15	0.05	0.15	bal
2025	0.50-1.2	1.0	3.9-5.0	0.40-1.2	0.05	0.10	. . .	0.25	. . .	. . .	. . .	0.15	0.05	0.15	bal
2034	0.10	0.12	4.2-4.8	0.8-1.3	1.3-1.9	0.05	. . .	0.20	. . .	. . .	0.08-0.15 Zr	0.15	0.05	0.15	bal
2036	0.50	0.50	2.2-3.0	0.10-0.40	0.30-0.6	0.10	. . .	0.25	. . .	. . .	. . .	0.15	0.05	0.15	bal
2037	0.50	0.50	1.4-2.2	0.10-0.40	0.30-0.8	0.10	. . .	0.25	. . .	0.05	. . .	0.15	0.05	0.15	bal
2038	0.50-1.3	0.6	0.8-1.8	0.10-0.40	0.40-1.0	0.20	. . .	0.50	0.05	0.05	. . .	0.15	0.05	0.15	bal
2048	0.15	0.20	2.8-3.8	0.20-0.6	1.2-1.8	. . .	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
X2080	0.10	0.20	3.3-4.1	0.25	1.5-2.2	. . .	. . .	0.10	. . .	. . .	0.08-0.25 Zr(i)	. . .	0.05	0.15	bal
2090	0.10	0.12	2.4-3.0	0.05	0.25	0.05	. . .	0.10	. . .	. . .	0.08-0.15 Zr(j)	0.15	0.05	0.15	bal
2091	0.20	0.30	1.8-2.5	0.10	1.1-1.9	0.10	. . .	0.25	. . .	. . .	0.04-0.16 Zr(k)	0.10	0.05	0.15	bal
2094	0.12	0.15	4.4-5.2	0.25	0.025-0.8	. . .	. . .	0.25	. . .	. . .	0.04-0.18 Zr(l)	0.10	0.05	0.15	bal
2095	0.12	0.15	3.9-4.6	0.25	0.25-0.8	. . .	. . .	0.25	. . .	. . .	0.04-0.18 Zr(m)	0.10	0.05	0.15	bal
2195	0.12	0.15	3.7-4.3	0.25	0.25-0.8	. . .	. . .	0.25	. . .	. . .	0.08-0.16 Zr(n)	0.10	0.05	0.15	bal
X2096	0.12	0.15	2.3-3.0	0.25	0.25-0.8	. . .	. . .	0.25	. . .	. . .	0.04-0.18 Zr(o)	0.10	0.05	0.15	bal
2097	0.12	0.15	2.5-3.1	0.10-0.6	0.35	. . .	. . .	0.35	. . .	. . .	0.08-0.16 Zr(p)	0.15	0.05	0.15	bal

2197	0.10	0.10	2.5-3.1	0.10-0.50	0.25	. . .	. . .	0.05	. . .	. . .	0.08-0.15 Zr(q)	0.12	0.05	0.15	bal
3002	0.08	0.10	0.15	0.05-0.25	0.05-0.20	. . .	. . .	0.05	. . .	0.05	. . .	0.03	0.03	0.10	bal
3102	0.40	0.7	0.10	0.05-0.40	. . .	. . .	. . .	0.30	. . .	. . .	. . .	0.10	0.05	0.15	bal
3003	0.6	0.7	0.05-0.20	1.0-1.5	. . .	. . .	. . .	0.10	. . .	. . .	. . .	. . .	0.05	0.15	bal
3303	0.6	0.7	0.05-0.20	1.0-1.5	. . .	. . .	. . .	0.30	. . .	. . .	. . .	. . .	0.05	0.15	bal
3004	0.30	0.7	0.25	1.0-1.5	0.8-1.3	. . .	. . .	0.25	. . .	. . .	. . .	. . .	0.05	0.15	bal
3104	0.6	0.8	0.05-0.25	0.8-1.4	0.8-1.3	. . .	. . .	0.25	0.05	0.05	. . .	0.10	0.05	0.15	bal
3204	0.30	0.7	0.10-0.25	0.8-1.5	0.8-1.5	. . .	. . .	0.25	. . .	. . .	. . .	. . .	0.05	0.15	bal
3005	0.6	0.7	0.30	1.0-1.5	0.20-0.6	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
3105	0.6	0.7	0.30	0.30-0.8	0.20-0.8	0.20	. . .	0.40	. . .	. . .	. . .	0.10	0.05	0.15	bal
3006	0.50	0.7	0.10-0.30	0.50-0.8	0.30-0.6	0.20	. . .	0.15-0.40	. . .	. . .	. . .	0.10	0.05	0.15	bal
3007	0.50	0.7	0.05-0.30	0.30-0.8	0.6	0.20	. . .	0.40	. . .	. . .	. . .	0.10	0.05	0.15	bal
3107	0.6	0.7	0.05-0.15	0.40-0.9	. . .	. . .	. . .	0.20	. . .	. . .	. . .	0.10	0.05	0.15	bal
3307	0.6	0.8	0.30	0.50-0.9	0.30	0.20	. . .	0.40	. . .	. . .	. . .	0.10	0.05	0.15	bal
3009	1.0-1.8	0.7	0.10	1.2-1.8	0.10	0.05	0.05	0.05	. . .	. . .	0.10 Zr	0.10	0.05	0.15	bal
3010	0.10	0.20	0.03	0.20-0.9	. . .	0.05-0.40	. . .	0.05	. . .	0.05	. . .	0.05	0.03	0.10	bal

3011	0.40	0.7	0.05-0.20	0.8-1.2	. . .	0.10-0.40	. . .	0.10	. . .	. . .	0.10-0.30 Zr	0.10	0.05	0.15	bal
3015	0.6	0.8	0.30	0.50-0.9	0.20-0.7	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
3016	0.6	0.8	0.30	0.50-0.9	0.50-0.8	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
4004	9.0-10.5	0.8	0.25	0.10	1.0-2.0	. . .	. . .	0.20	. . .	. . .	. . .	. . .	0.05	0.15	bal
4104	9.0-10.5	0.8	0.25	0.10	1.0-2.0	. . .	. . .	0.20	. . .	. . .	0.02-0.20 Bi	. . .	0.05	0.15	bal
4008	6.5-7.5	0.09	0.05	0.05	0.30-0.45	. . .	. . .	0.05	. . .	. . .	(a)	0.04-0.15	0.05	0.15	bal
4009	4.5-5.5	0.20	1.0-1.5	0.10	0.45-0.6	. . .	. . .	0.10	. . .	. . .	(a)	0.20	0.05	0.15	bal
4010	6.5-7.5	0.20	0.20	0.10	0.30-0.45	. . .	. . .	0.10	. . .	. . .	(a)	0.20	0.05	0.15	bal
4011	6.5-7.5	0.20	0.20	0.10	0.45-0.7	. . .	. . .	0.10	. . .	. . .	0.04-0.07 Be	0.04-0.20	0.05	0.15	bal
4013	3.5-4.5	0.35	0.05-0.20	0.03	0.05-0.20	. . .	. . .	0.05	. . .	. . .	(r)	0.02	0.05	0.15	bal
4032	11.0-13.5	1.0	0.50-1.3	. . .	0.8-1.3	0.10	0.50-1.3	0.25	. . .	. . .	. . .	. . .	0.05	0.15	bal
4043	4.5-6.0	0.8	0.30	0.05	0.05	. . .	. . .	0.10	. . .	. . .	(a)	0.20	0.05	0.15	bal
4343	6.8-8.2	0.8	0.25	0.10	. . .	. . .	. . .	0.20	. . .	. . .	. . .	. . .	0.05	0.15	bal
4543	5.0-7.0	0.50	0.10	0.05	0.10-0.40	0.05	. . .	0.10	. . .	. . .	. . .	0.10	0.05	0.15	bal
4643	3.6-4.6	0.8	0.10	0.05	0.10-0.30	. . .	. . .	0.10	. . .	. . .	(a)	0.15	0.05	0.15	bal
4044	7.8-9.2	0.8	0.25	0.10	. . .	. . .	. . .	0.20	. . .	. . .	. . .	. . .	0.05	0.15	bal

4045	9.0-11.0	0.8	0.30	0.05	0.05	. . .	. . .	0.10	. . .	. . .	. . .	0.20	0.05	0.15	bal
4145	9.3-10.7	0.8	3.3-4.7	0.15	0.15	0.15	. . .	0.20	. . .	. . .	(a)	. . .	0.05	0.15	bal
4047	11.0-13.0	0.8	0.30	0.15	0.10	. . .	. . .	0.20	. . .	. . .	(a)	. . .	0.05	0.15	bal
4147	11.0-13.0	0.8	0.25	0.10	0.10-0.50	. . .	. . .	0.20	. . .	. . .	(a)	. . .	0.05	0.15	bal
4048(s)	9.3-10.7	0.8	3.3-4.7	0.07	0.07	0.07	. . .	9.3-10.7	. . .	·.	(a)	. . .	0.05	0.15	bal
5005	0.30	0.7	0.20	0.20	0.50-1.1	0.10	. . .	0.25	. . .	. . .	. . .	. . .	0.05	0.15	bal
5205	0.15	0.7	0.03-0.10	0.10	0.6-1.0	0.10	. . .	0.05	. . .	. . .	. . .	. . .	0.05	0.15	bal
5006	0.40	0.8	0.10	0.40-0.8	0.8-1.3	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
5010	0.40	0.7	0.25	0.10-0.30	0.20-0.6	0.15	. . .	0.30	. . .	. . .	. . .	0.10	0.05	0.15	bal
5016	0.25	0.6	0.20	0.40-0.7	1.4-1.9	0.10	. . .	0.15	. . .	. . .	. . .	0.05	0.05	0.15	bal
5017	0.40	0.7	0.18-0.28	0.6-0.8	1.9-2.2	. . .	. . .	. . .	. . .	. . .	. . .	0.09	0.05	0.15	bal
5040	0.30	0.7	0.25	0.9-1.4	1.0-1.5	0.10-0.30	. . .	0.25	. . .	. . .	. . .	. . .	0.05	0.15	bal
5042	0.20	0.35	0.15	0.20-0.50	3.0-4.0	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
5043	0.40	0.7	0.05-0.35	0.7-1.2	0.7-1.3	0.05	. . .	0.25	0.05	0.05	. . .	0.10	0.05	0.15	bal
5349	0.40	0.7	0.18-0.28	0.6-1.2	1.7-2.6	. . .	. . .	. . .	. . .	. . .	. . .	0.09	0.05	0.15	bal
5050	0.40	0.7	0.20	0.10	1.1-1.8	0.10	. . .	0.25	. . .	. . .	. . .	. . .	0.05	0.15	bal

5250	0.08	0.10	0.10	0.05-0.15	1.3-1.8	. . .	·	0.05	0.03	0.05	. . .	. . .	0.03	0.10	bal
5051	0.40	0.7	0.25	0.20	1.7-2.2	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
5151	0.20	0.35	0.15	0.10	1.5-2.1	0.10	. . .	0.15	. . .	. . .	. . .	0.10	0.05	0.15	bal
5351	0.08	0.10	0.10	0.10	1.6-2.2	. . .	. . .	0.05	. . .	0.05	. . .	. . .	0.03	0.10	bal
5451	0.25	0.40	0.10	0.10	1.8-2.4	0.15-0.35	0.05	0.10	. . .	. . .	. . .	0.05	0.05	0.15	bal
5052	0.25	0.40	0.10	0.10	2.2-2.8	0.15-0.35	. . .	0.10	. . .	. . .	. . .	. . .	0.05	0.15	bal
5252	0.08	0.10	0.10	0.10	2.2-2.8	. . .	. . .	0.05	. . .	0.05	. . .	. . .	0.03	0.10	bal
5352	0.45 Si + Fe		0.10	0.10	2.2-2.8	0.10	. . .	0.10	. . .	. . .	. . .	0.10	0.05	0.15	bal
5552	0.04	0.05	0.10	0.10	2.2-2.8	. . .	. . .	0.05	. . .	0.05	. . .	. . .	0.03	0.10	bal
5652	0.40 Si + Fe		0.04	0.01	2.2-2.8	0.15-0.35	. . .	0.10	. . .	. . .	. . .	. . .	0.05	0.15	bal
5154	0.25	0.40	0.10	0.10	3.1-3.9	0.15-0.35	. . .	0.20	. . .	. . .	(a)	0.20	0.05	0.15	bal
5254	0.45 Si + Fe		0.05	0.01	3.1-3.9	0.15-0.35	. . .	0.20	. . .	. . .	. . .	0.05	0.05	0.15	bal
5454	0.25	0.40	0.10	0.50-1.0	2.4-3.0	0.05-0.20	. . .	0.25	. . .	. . .	. . .	0.20	0.05	0.15	bal
5554	0.25	0.40	0.10	0.50-1.0	2.4-3.0	0.05-0.20	. . .	0.25	. . .	. . .	(a)	0.05-0.20	0.05	0.15	bal
5654	0.45 Si + Fe		0.05	0.01	3.1-3.9	0.15-0.35	. . .	0.20	. . .	. . .	(a)	0.05-0.15	0.05	0.15	bal
5754	0.40	0.40	0.10	0.50	2.6-3.6	0.30	. . .	0.20	. . .	. . .	0.10-0.6 Mn + Cr	0.15	0.05	0.15	bal

5954	0.25	0.40	0.10	0.10	3.3-4.1	0.10	. . .	0.20	. . .	. . .	. . .	0.20	0.05	0.15	bal
5056	0.30	0.40	0.10	0.05-0.20	4.5-5.6	0.05-0.20	. . .	0.10	. . .	. . .	. . .	. . .	0.05	0.15	bal
5356	0.25	0.40	0.10	0.05-0.20	4.5-5.5	0.05-0.20	. . .	0.10	. . .	. . .	(a)	0.06-0.20	0.05	0.15	bal
5456	0.25	0.40	0.10	0.50-1.0	4.7-5.5	0.05-0.20	. . .	0.25	. . .	. . .	. . .	0.20	0.05	0.15	bal
5556	0.25	0.40	0.10	0.50-1.0	4.7-5.5	0.05-0.20	. . .	0.25	. . .	. . .	(a)	0.05-0.20	0.05	0.15	bal
5357	0.12	0.17	0.20	0.15-0.45	0.8-1.2	. . .	. . .	0.05	. . .	. . .	. . .	. . .	0.05	0.15	bal
5457	0.08	0.10	0.20	0.15-0.45	0.8-1.2	. . .	. . .	0.05	. . .	0.05	. . .	. . .	0.03	0.10	bal
5557	0.10	0.12	0.15	0.10-0.40	0.40-0.8	. . .	. . .	. . .	. . .	0.05	. . .	. . .	0.03	0.10	bal
5657	0.08	0.10	0.10	0.03	0.6-1.0	. . .	. . .	0.05	0.03	0.05	. . .	. . .	0.02	0.05	bal
5180	0.35 Si + Fe		0.10	0.20-0.7	3.5-4.5	0.10	. . .	1.7-2.8	. . .	. . .	0.08-0.25 Zr(a)	0.06-0.20	0.05	0.15	bal
5082	0.20	0.35	0.15	0.15	4.0-5.0	0.15	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
5182	0.20	0.35	0.15	0.20-0.50	4.0-5.0	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
5083	0.40	0.40	0.10	0.40-1.0	4.0-4.9	0.05-0.25	. . .	0.25	. . .	. . .	. . .	0.15	0.05	0.15	bal
5183	0.40	0.40	0.10	0.50-1.0	4.3-5.2	0.05-0.25	. . .	0.25	. . .	. . .	(a)	0.15	0.05	0.15	bal
5086	0.40	0.50	0.10	0.20-0.7	3.5-4.5	0.05-0.25	. . .	0.25	. . .	. . .	. . .	0.15	0.05	0.15	bal
5091	0.20	0.30	. . .	. . .	3.7-4.2	. . .	. . .	. . .	. . .	. . .	(t)	. . .	0.05	0.15	bal

6101	0.30-0.7	0.50	0.10	0.03	0.35-0.8	0.03	. . .	0.10	. . .	. . .	0.06 B	. . .	0.03	0.10	bal
6201	0.50-0.9	0.50	0.10	0.03	0.6-0.9	0.03	. . .	0.10	. . .	. . .	0.06 B	. . .	0.03	0.10	bal
6301	0.50-0.9	0.7	0.10	0.15	0.6-0.9	0.10	. . .	0.25	. . .	. . .	. . .	0.15	0.05	0.15	bal
6003	0.35-1.0	0.6	0.10	0.8	0.8-1.5	0.35	. . .	0.20	. . .	. . .	. . .	0.10	0.05	0.15	bal
6004	0.30-0.6	0.10-0.30	0.10	0.20-0.6	0.40-0.7	. . .	. . .	0.05	. . .	. . .	. . .	. . .	0.05	0.15	bal
6005	0.6-0.9	0.35	0.10	0.10	0.40-0.6	0.10	. . .	0.10	. . .	. . .	. . .	0.10	0.05	0.15	bal
6005A	0.50-0.9	0.35	0.30	0.50	0.40-0.7	0.30	. . .	0.20	. . .	. . .	0.12-0.50 Mn + Cr	0.10	0.05	0.15	bal
6105	0.6-1.0	0.35	0.10	0.10	0.45-0.8	0.10	. . .	0.10	. . .	. . .	. . .	0.10	0.05	0.15	bal
6205	0.6-0.9	0.7	0.20	0.05-0.15	0.40-0.6	0.05-0.15	. . .	0.25	. . .	. . .	0.05-0.15 Zr	0.15	0.05	0.15	bal
6006	0.20-0.6	0.35	0.15-0.30	0.05-0.20	0.45-0.9	0.10	. . .	0.10	. . .	. . .	. . .	0.10	0.05	0.15	bal
6206	0.35-0.7	0.35	0.20-0.50	0.13-0.30	0.45-0.8	0.10	. . .	0.20	. . .	. . .	. . .	0.10	0.05	0.15	bal
6306	0.20-0.6	0.10	0.05-0.16	0.10-0.0	0.45-0.9	. . .	. . .	0.05	. . .	. . .	. . .	0.05	0.05	0.15	bal
6007	0.9-1.4	0.7	0.20	0.05-0.25	0.6-0.9	0.05-0.25	. . .	0.25	. . .	. . .	0.05-0.20 Zr	0.15	0.05	0.15	bal
6009	0.6-1.0	0.50	0.15-0.6	0.20-0.8	0.40-0.8	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
6010	0.8-1.2	0.50	0.15-0.6	0.20-0.8	0.6-1.0	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
6110	0.7-1.5	0.8	0.20-0.7	0.20-0.7	0.50-1.1	0.04-0.25	. . .	0.30	. . .	. . .	. . .	0.15	0.05	0.15	bal

6011	0.6-1.2	1.0	0.40-0.9	0.8	0.6-1.2	0.30	0.20	1.5	. . .	. . .	. . .	0.20	0.05	0.15	bal
6111	0.6-1.1	0.40	0.50-0.9	0.10-0.45	0.50-1.0	0.10	. . .	0.15	. . .	. . .	. . .	0.10	0.05	0.15	bal
6013	0.6-1.0	0.50	0.6-1.1	0.20-0.8	0.8-1.2	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
6113	0.6-1.0	0.30	0.6-1.1	0.10-0.6	0.8-1.2	0.10	. . .	0.25	. . .	. . .	(u)	0.10	0.05	0.15	bal
6017	0.55-0.7	0.15-0.30	0.05-0.20	0.10	0.45-0.6	0.10	. . .	0.05	. . .	. . .	. . .	0.05	0.05	0.15	bal
6151	0.6-1.2	1.0	0.35	0.20	0.45-0.8	0.15-0.35	. . .	0.25	. . .	. . .	. . .	0.15	0.05	0.15	bal
6351	0.7-1.3	0.50	0.10	0.40-0.8	0.40-0.8	. . .	. . .	0.20	. . .	. . .	. . .	0.20	0.05	0.15	bal
6951	0.20-0.50	0.8	0.15-0.40	0.10	0.40-0.8	. . .	. . .	0.20	. . .	. . .	. . .	. . .	0.05	0.15	bal
6053	(v)	0.35	0.10	. . .	1.1-1.4	0.15-0.35	. . .	0.10	. . .	. . .	. . .	. . .	0.05	0.15	bal
6253	(v)	0.50	0.10	. . .	1.0-1.5	0.04-0.35	. . .	1.6-2.4	. . .	. . .	. . .	. . .	0.05	0.15	bal
6060	0.30-0.6	0.10-0.30	0.10	0.10	0.35-0.6	0.05	. . .	0.15	. . .	. . .	. . .	0.10	0.05	0.15	bal
6160	0.30-0.6	0.15	0.20	0.05	0.35-0.6	0.05	. . .	0.05	. . .	. . .	. . .	. . .	0.05	0.15	bal
6061	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	. . .	0.25	. . .	. . .	. . .	0.15	0.05	0.15	bal
6162	0.40-0.8	0.50	0.20	0.10	0.7-1.1	0.10	. . .	0.25	. . .	. . .	. . .	0.10	0.05	0.15	bal
6262	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.14	. . .	0.25	. . .	. . .	(w)	0.15	0.05	0.15	bal
6063	0.20-0.6	0.35	0.10	0.10	0.45-0.9	0.10	. . .	0.10	. . .	. . .	. . .	0.10	0.05	0.15	bal

6463	0.20-0.6	0.15	0.20	0.05	0.45-0.9	. . .	. . .	0.05	. . .	. . .	. . .	. . .	0.05	0.15	bal
6763	0.20-0.6	0.08	0.04-0.16	0.03	0.45-0.9	. . .	. . .	0.03	. . .	0.05	. . .	. . .	0.03	0.10	bal
6066	0.9-1.8	0.50	0.7-1.2	0.6-1.1	0.8-1.4	0.40	. . .	0.25	. . .	. . .	. . .	0.20	0.05	0.15	bal
6070	1.0-1.7	0.50	0.15-0.40	0.40-1.0	0.50-1.2	0.10	. . .	0.25	. . .	. . .	. . .	0.15	0.05	0.15	bal
6091	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.15	. . .	0.25	. . .	. . .	(u)	0.15	0.05	0.15	bal
6092	0.40-0.8	0.30	0.7-1.0	0.15	0.8-1.2	0.15	. . .	0.25	. . .	. . .	(u)	0.15	0.05	0.15	bal
7001	0.35	0.40	1.6-2.6	0.20	2.6-3.4	0.18-0.35	. . .	6.8-8.0	. . .	. . .	. . .	0.20	0.05	0.15	bal
7004	0.25	0.35	0.05	0.20-0.7	1.0-2.0	0.05	. . .	3.8-4.6	. . .	. . .	0.10-0.20 Zr	0.05	0.05	0.15	bal
7005	0.35	0.40	0.10	0.20-0.7	1.0-1.8	0.06-0.20	. . .	4.0-5.0	. . .	. . .	0.08-0.20 Zr	0.01-0.06	0.05	0.15	bal
7008	0.10	0.10	0.05	0.05	0.7-1.4	0.12-0.25	. . .	4.5-5.5	. . .	. . .	. . .	0.05	0.05	0.10	bal
7108	0.10	0.10	0.05	0.05	0.7-1.4	. . .	. . .	4.5-5.5	. . .	. . .	0.12-0.25 Zr	0.05	0.05	0.15	bal
7011	0.15	0.20	0.05	0.10-0.30	1.0-1.6	0.05-0.20	. . .	4.0-5.5	. . .	. . .	. . .	0.05	0.05	0.15	bal
7013	0.6	0.7	0.10	1.0-1.5	. . .	. . .	. . .	1.5-2.0	. . .	. . .	. . .	. . .	0.05	0.15	bal
7016	0.10	0.12	0.45-1.0	0.03	0.8-1.4	. . .	. . .	4.0-5.0	. . .	0.05	. . .	0.03	0.03	0.10	bal
7116	0.15	0.30	0.50-1.1	0.05	0.8-1.4	. . .	. . .	4.2-5.2	0.03	0.05	. . .	0.05	0.05	0.15	bal
7021	0.25	0.40	0.25	0.10	1.2-1.8	0.05	. . .	5.0-6.0	. . .	. . .	0.08-0.18 Zr	0.10	0.05	0.15	bal

7029	0.10	0.12	0.50-0.9	0.03	1.3-2.0	. . .	. . .	4.2-5.2	. . .	0.05	. . .	0.05	0.03	0.10	bal
7129	0.15	0.30	0.50-0.9	0.10	1.3-2.0	0.10	. . .	4.2-5.2	0.03	0.05	. . .	0.05	0.05	0.15	bal
7229	0.06	0.08	0.50-0.9	0.03	1.3-2.0	. . .	. . .	4.2-5.2	. . .	0.05	. . .	0.05	0.03	0.10	bal
7031	0.30	0.8-1.4	0.10	0.10-0.40	0.10	. . .	. . .	0.8-1.8	. . .	. . .	. . .	. . .	0.05	0.15	bal
7039	0.30	0.40	0.10	0.10-0.40	2.3-3.3	0.15-0.25	. . .	3.5-4.5	. . .	. . .	. . .	0.10	0.05	0.15	bal
7046	0.20	0.40	0.25	0.30	1.0-1.6	0.20	. . .	6.6-7.6	. . .	. . .	0.10-0.18 Zr	0.06	0.05	0.15	bal
7146	0.20	0.40	. . .	. . .	1.0-1.6	. . .	. . .	6.6-7.6	. . .	. . .	0.10-0.18 Zr	0.06	0.05	0.15	bal
7049	0.25	0.35	1.2-1.9	0.20	2.0-2.9	0.10-0.22	. . .	7.2-8.2	. . .	. . .	. . .	0.10	0.05	0.15	bal
7149	0.15	0.20	1.2-1.9	0.20	2.0-2.9	0.10-0.22	. . .	7.2-8.2	. . .	. . .	. . .	0.10	0.05	0.15	bal
7249	0.10	0.12	1.3-1.9	0.10	2.0-2.4	0.12-0.18	. . .	7.5-8.2	. . .	. . .	. . .	0.06	0.05	0.15	bal
7050	0.12	0.15	2.0-2.6	0.10	1.9-2.6	0.04	. . .	5.7-6.7	. . .	. . .	0.08-0.15 Zr	0.06	0.05	0.15	bal
7150	0.12	0.15	1.9-2.5	0.10	2.0-2.7	0.04	. . .	5.9-6.9	. . .	. . .	0.08-0.15 Zr	0.06	0.05	0.15	bal
7055	0.10	0.15	2.0-2.6	0.05	1.8-2.3	0.04	. . .	7.6-8.4	. . .	. . .	0.08-0.25 Zr	0.06	0.05	0.15	bal
7064	0.12	0.15	1.8-2.4	. . .	1.9-2.9	0.06-0.25	. . .	6.8-8.0	. . .	. . .	0.10-0.50 Zr(x)	. . .	0.05	0.15	bal
7072	0.7 Si + Fe		0.10	0.10	0.10	. . .	. . .	0.8-1.3	. . .	. . .	. . .	. . .	0.05	0.15	bal
7472	0.25	0.6	0.05	0.05	0.9-1.5	. . .	. . .	1.3-1.9	. . .	. . .	. . .	. . .	0.05	0.15	bal

7075	0.40	0.50	1.2-2.0	0.30	2.1-2.9	0.18-0.28	. . .	5.1-6.1	. . .	. . .	(y)	0.20	0.05	0.15	bal
7175	0.15	0.20	1.2-2.0	0.10	2.1-2.9	0.18-0.28	. . .	5.1-6.1	. . .	. . .	. . .	0.10	0.05	0.15	bal
7475	0.10	0.12	1.2-1.9	0.06	1.9-2.6	0.18-0.25	. . .	5.2-6.2	. . .	. . .	. . .	0.06	0.05	0.15	bal
7076	0.40	0.6	0.30-1.0	0.30-0.8	1.2-2.0	. . .	. . .	7.0-8.0	. . .	. . .	. . .	0.20	0.05	0.15	bal
7277	0.50	0.7	0.8-1.7	. . .	1.7-2.3	0.18-0.35	. . .	3.7-4.3	. . .	. . .	. . .	0.10	0.05	0.15	bal
7178	0.40	0.50	1.6-2.4	0.30	2.4-3.1	0.18-0.28	. . .	6.3-7.3	. . .	. . .	. . .	0.20	0.05	0.15	bal
7090	0.12	0.15	0.6-1.3	. . .	2.0-3.0	. . .	. . .	7.3-8.7	. . .	. . .	1.0-1.9 Co(z)	. . .	0.05	0.15	bal
7091	0.12	0.15	1.1-1.8	. . .	2.0-3.0	. . .	. . .	5.8-7.1	. . .	. . .	0.20-0.60 Co(z)	. . .	0.05	0.15	bal
7093	0.12	0.15	1.1-1.9	. . .	2.0-3.0	. . .	0.04-0.16	8.3-9.7	. . .	. . .	0.08-0.20 Zr(u)	. . .	0.05	0.15	bal
8001	0.17	0.45-0.7	0.15	. . .	. . .	. . .	0.9-1.3	0.05	. . .	. . .	(aa)	. . .	0.05	0.15	bal
8006	0.40	1.2-2.0	0.30	0.30-1.0	0.10	. . .	. . .	0.10	. . .	. . .	. . .	. . .	0.05	0.15	bal
8007	0.40	1.2-2.0	0.10	0.30-1.0	0.10	. . .	. . .	0.8-1.8	. . .	. . .	. . .	. . .	0.05	0.15	bal
8009	1.7-1.9	8.4-8.9	. . .	0.10	. . .	0.10	. . .	0.25	. . .	1.1-1.5	(bb)	0.10	0.05	0.15	bal
8010	0.40	0.35-0.7	0.10-0.30	0.10-0.8	0.10-0.50	0.20	. . .	0.40	. . .	. . .	. . .	0.10	0.05	0.15	bal
8111	0.30-1.1	0.40-1.0	0.10	0.10	0.05	0.05	. . .	0.10	. . .	. . .	. . .	0.08	0.05	0.15	bal
8112	1.0	1.0	0.40	0.6	0.7	0.20	. . .	1.0	. . .	. . .	. . .	0.20	0.05	0.15	bal

8014	0.30	1.2-1.6	0.20	0.20-0.6	0.10	. . .	. . .	0.10	. . .	. . .	. . .	0.10	0.05	0.15	bal
8015	0.30	0.8-1.4	0.10	0.10-0.40	0.10	. . .	. . .	0.10	. . .	. . .	. . .	. . .	0.05	0.15	bal
8017	0.10	0.55-0.8	0.10-0.20	. . .	0.01-0.05	. . .	. . .	0.05	. . .	. . .	0.04 B, 0.003 Li	. . .	0.03	0.10	bal
X8019	0.20	7.3-9.3	. . .	0.05	. . .	. . .	. . .	0.05	. . .	. . .	(cc)	0.05	0.05	0.15	bal
8020	0.10	0.10	0.005	0.005	. . .	. . .	. . .	0.005	. . .	0.05	(dd)	. . .	0.03	0.10	bal
8022	1.2-1.4	6.2-6.8	. . .	0.10	. . .	0.10	. . .	0.25	. . .	0.40-0.8	(ee)	0.10	0.05	0.15	bal
8030	0.10	0.30-0.8	0.15-0.30	. . .	0.05	. . .	. . .	0.05	. . .	. . .	0.001-0.04 B	. . .	0.03	0.10	bal
8130	0.15(ff)	0.40-1.0(ff)	0.05-0.15	. . .	. . .	. . .	. . .	0.10	. . .	. . .	. . .	. . .	0.03	0.10	bal
8040	1.0 Si + Fe		0.20	0.05	. . .	. . .	. . .	0.20	. . .	. . .	0.10-0.30 Zr	. . .	0.05	0.15	bal
8076	0.10	0.6-0.9	0.04	. . .	0.08-0.22	. . .	. . .	0.05	. . .	. . .	0.04 B	. . .	0.03	0.10	bal
8176	0.03-0.15	0.40-1.0	. . .	. . .	. . .	. . .	. . .	0.10	0.03	. . .	. . .	. . .	0.05	0.15	bal
8077	0.10	0.10-0.40	0.05	. . .	0.10-0.30	. . .	. . .	0.05	. . .	. . .	0.05 B(gg)	. . .	0.03	0.10	bal
8177	0.10	0.25-0.45	0.04	. . .	0.04-0.12	. . .	. . .	0.05	. . .	. . .	0.04 B	. . .	0.03	0.10	bal
8079	0.05-0.30	0.7-1.3	0.05	. . .	. . .	. . .	. . .	0.10	. . .	. . .	. . .	. . .	0.05	0.15	bal
8280	1.0-2.0	0.7	0.7-1.3	0.10	. . .	. . .	0.20-0.7	0.05	. . .	. . .	5.5-7.0 Sn	0.10	0.05	0.15	bal
8081	0.7	0.7	0.7-1.3	0.10	. . .	. . .	. . .	0.05	. . .	. . .	18.0-22.0 Sn	0.10	0.05	0.15	bal

8090	0.20	0.30	1.0-1.6	0.10	0.6-1.3	0.10	. . .	0.25	. . .	. . .	0.04-0.16 Zr(hh)	0.10	0.05	0.15	bal

Source: Aluminum Association Inc.

(a) 0.0008% max Be for welding electrode and filler wire only.

(b) 0.14% max Si + Fe.

(c) 0.6%max O.

(d) 0.20-0.6% Bi, 0.20-0.6% Pb.

(e) 0.20-0.8%Bi, 0.10-0.50% Sn.

(f) 0.20-0.7%Bi, 0.20-0.6% Sn.

(g) A Zr+ Ti limit of 0.20% max can be used with this alloy designation for extruded and forged products only, but only when the supplier and purchaser have mutually so agreed.

(h) 0.40% max Si + Fe.

(i) 0.005% max Be, 0.20-0.50%O.

(j) 1.9-2.6% Li.

(k) 1.7-2.3% Li.

(l) 0.25-0.6% Ag, 0.7-1.4% Li.

(m) 0.25-0.6% Ag, 0.7-1.5%Li.

(n) 0.25-0.6% Ag, 0.8-1.2%Li.

(o) 0.25-0.6% Ag, 1.3-1.9%Li.

(p) 1.2-1.8% Li.

(q) 1.3-1.7% Li.

(r) 0.6-1.5% Bi, 0.05% max Cd.

(s) Formerly inactive alloy 4245 reactivated as 4048.

(t) 1.0-1.3% C, 1.2-1.4%Li, 0.20-0.7% O.

(u) 0.05-0.50%O.

(v) 45-65% of actual Mg.

(w) 0.40-0.7% Bi, 0.40-0.7%Pb.

(x) 0.10-0.40% Co, 0.05-0.30%O.

(y) A Zr + Ti limit of 0.25%max can be used with this alloy designation for extruded and forged products only, but only when the supplier and purchaser have mutually so agreed.

(z) 0.20-0.50% O.

(aa) 0.001% max B, 0.003% max Cd, 0.001% max Co, 0.008% max Li.

(bb) 0.30% max O.

(cc) 3.5-4.5% Ce, 0.20-0.50%O.

(dd) 0.10-0.50% Bi, 0.10-0.25%Sn.

(ee) 0.05-0.20% O.

(ff) 1.0% max Si + Fe.

(gg) 0.02-0.08% Zr.

(hh) 2.2-2.7% Li.

Table 2 Composition limits for unalloyed and alloyed aluminum castings (*xxx*.0) and ingots (*xxx*.1 or *xxx*.2)

Designation		Composition, wt%											Others		Al, min
AA No.	**Former**	**Products(a)**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Ni**	**Zn**	**Ti**	**Sn**	**Each**	**Total**	
100.1	. . .	Ingot	0.15	0.6-0.8	0.10	(b)	. . .	(b)	. . .	0.05	(b)	. . .	0.03(b)	0.10	99.00
130.1	. . .	Ingot	(c)	(c)	0.10	(b)	. . .	(b)	. . .	0.05	(b)	. . .	0.03(b)	0.10	99.30
150.1	. . .	Ingot	(d)	(d)	0.05	(b)	. . .	(b)	. . .	0.05	(b)	. . .	0.03	0.10	99.50
160.1	. . .	Ingot	0.10(d)	0.25(d)	. . .	(b)	. . .	(b)	. . .	0.05	(b)	. . .	0.03	0.10	99.60
170.1	. . .	Ingot	(e)	(e)	. . .	(b)	. . .	(b)	. . .	0.05	(b)	. . .	0.03(b)	0.10	99.70
201.0	. . .	S	0.10	0.15	4.0-5.2	0.20-0.50	0.15-0.55	. . .	. . .	. . .	0.15-0.35	. . .	0.05(f)	0.10	bal
201.2	. . .	Ingot	0.10	0.10	4.0-5.2	0.20-0.50	0.20-0.55	. . .	. . .	. . .	0.15-0.35	. . .	0.05(f)	0.10	bal
A201.0	. . .	S	0.05	0.10	4.0-5.0	0.20-0.40	0.15-0.35	. . .	. . .	. . .	0.15-0.35	. . .	0.03(f)	0.10	bal
A201.1	A201.2	Ingot	0.05	0.07	4.0-5.0	0.20-0.40	0.20-0.35	. . .	. . .	. . .	0.15-0.35	. . .	0.03(f)	0.10	bal
B201.0	. . .	S	0.05	0.05	4.5-5.0	0.20-0.50	0.25-0.35	. . .	. . .	. . .	0.15-0.35	. . .	0.05(g)	0.15	bal

203.0	Hiduminium 350	S	0.30	0.50	4.5-5.5	0.20-0.30	0.10	. . .	1.3-1.7	0.10	0.5-0.25(h)	. . .	0.05(i)	0.20	bal
203.2	Hiduminium 350	Ingot	0.20	0.35	4.8-5.2	0.20-0.30	0.10	. . .	1.3-1.7	0.10	0.15-0.25(h)	. . .	0.05(i)	0.20	bal
204.0	A-U5GT	S, P	0.20	0.35	4.2-5.0	0.10	0.15-0.35	. . .	0.05	0.10	0.15-0.30	0.05	0.05	0.15	bal
204.2	A-U5GT	Ingot	0.15	0.10-0.20	4.2-4.9	0.05	0.20-0.35	. . .	0.03	0.05	0.15-0.25	0.05	0.05	0.15	bal
206.0	. . .	S, P	0.10	0.15	4.2-5.0	0.20-0.50	0.15-0.35	. . .	0.05	0.10	0.15-0.30	0.05	0.05	0.15	bal
206.2	. . .	Ingot	0.10	0.10	4.2-5.0	0.20-0.50	0.20-0.35	. . .	0.03	0.05	0.15-0.25	0.05	0.05	0.15	bal
A206.0	. . .	S, P	0.05	0.10	4.2-5.0	0.20-0.50	0.15-0.35	. . .	0.05	0.10	0.15-0.30	0.05	0.05	0.15	bal
A206.2	. . .	Ingot	0.05	0.07	4.2-5.0	0.20-0.50	0.20-0.35	. . .	0.03	0.05	0.15-0.25	0.05	0.05	0.15	bal
240.0	A240.0, A140	S	0.50	0.50	7.0-9.0	0.30-0.7	5.5-6.5	. . .	0.30-0.7	0.10	0.20	. . .	0.05	0.15	bal
240.1	A240.1, A140	Ingot	0.50	0.40	7.0-9.0	0.30-0.7	5.6-6.5	. . .	0.30-0.7	0.10	0.20	. . .	0.05	0.15	bal
242.0	142	S, P	0.7	1.0	3.5-4.5	0.35	1.2-1.8	0.25	1.7-2.3	0.35	0.25	. . .	0.05	0.15	bal
242.1	142	Ingot	0.7	0.8	3.5-4.5	0.35	1.3-1.8	0.25	1.7-2.3	0.35	0.25	. . .	0.05	0.15	bal

242.2	142	Ingot	0.6	0.6	3.5-4.5	0.10	1.3-1.8	. . .	1.7-2.3	0.10	0.20	. . .	0.05	0.15	bal
A242.0	A142	S	0.6	0.8	3.7-4.5	0.10	1.2-1.7	0.15-0.25	1.8-2.3	0.10	0.07-0.20	. . .	0.05	0.15	bal
A242.1	A142	Ingot	0.6	0.6	3.7-4.5	0.10	1.3-1.7	0.15-0.25	1.8-2.3	0.10	0.07-0.20	. . .	0.05	0.15	bal
A242.2	A142	Ingot	0.35	0.6	3.7-4.5	0.10	1.3-1.7	0.15-0.25	1.8-2.3	0.10	0.07-0.20	. . .	0.05	0.15	bal
295.0	195	S	0.7-1.5	1.0	4.0-5.0	0.35	0.03	. . .	. . .	0.35	0.25	. . .	0.05	0.15	bal
295.1	195	Ingot	0.7-1.5	0.8	4.0-5.0	0.35	0.03	. . .	. . .	0.35	0.25	. . .	0.05	0.15	bal
295.2	195	Ingot	0.7-1.2	0.8	4.0-5.0	0.30	0.03	. . .	. . .	0.30	0.20	. . .. . .	0.05	0.15	bal
296.0	B295.0, B195	P	2.0-3.0	1.2	4.0-5.0	0.35	0.05	. . .	0.35	0.50	0.25	. . .	. . .	0.35	bal
296.1	B295.1, B195	Ingot	2.0-3.0	0.9	4.0-5.0	0.35	0.05	. . .	0.35	0.50	0.25	. . .	. . .	0.35	bal
296.2	B295.2, B195	Ingot	2.0-3.0	0.8	4.0-5.0	0.30	0.03	. . .	. . .	0.30	0.20	. . .	0.05	0.15	bal
301.0	. . .	. . .	9.5-1.5	0.8-1.5	3.0-3.5	0.50-0.8	0.25-0.50	. . .	1.0-1.5	0.05	0.20	. . .	0.03	0.10	bal
301.1	. . .	Ingot(j)	9.5-01.5	0.8-1.2	3.0-3.5	0.50-0.8	0.30-0.50	. . .	1.0-1.5	0.05	0.20	. . .	0.03	0.10	bal
302.0	. . .	. . .	9.5-10.5	0.25	2.8-3.2	. . .	0.7-1.2	. . .	1.0-1.5	0.05	0.20	. . .	0.03	0.10	bal
302.1	. . .	Ingot(j)	9.5-10.5	0.20	2.8-3.2	. . .	0.8-1.2	. . .	1.0-1.5	0.05	0.20	. . .	0.03	0.10	bal

303.0	. . .	. . .	9.5-10.5	0.8-1.5	0.20	0.50-0.8	0.45-0.7	. . .	. . .	0.05	0.20	. . .	0.03	0.10	bal
303.1	. . .	Ingot(j)	9.5-10.5	0.8-1.2	0.20	0.50-0.8	0.50-0.7	. . .	. . .	0.05	0.20	. . .	0.03	0.10	bal
308.0	A108	S, P	5.0-6.0	1.0	4.0-5.0	0.50	0.10	. . .	. . .	1.0	0.25	. . .	. . .	0.50	bal
308.1	A108	Ingot	5.0-6.0	0.8	4.0-5.0	0.50	0.10	. . .	. . .	1.0	0.25	. . .	. . .	0.50	bal
308.2	A108	Ingot	5.0-6.0	0.8	4.0-5.0	0.30	0.10	. . .	. . .	0.50	0.20	. . .	. . .	0.50	bal
318.0	. . .	S, P	5.5-6.5	1.0	3.0-4.0	0.50	0.10-0.6	. . .	0.35	1.0	0.25	. . .	. . .	0.50	bal
318.1	. . .	Ingot	5.5-6.5	0.8	3.0-4.0	0.50	0.15-0.6	. . .	0.35	0.9	0.25	. . .	. . .	0.50	bal
319.0	319, All Cast	S, P	5.5-6.5	1.0	3.0-4.0	0.50	0.10	. . .	0.35	1.0	0.25	. . .	. . .	0.50	bal
319.1	319, All Cast	Ingot	5.5-6.5	0.8	3.0-4.0	0.50	0.10	. . .	0.35	1.0	0.25	. . .	. . .	0.50	bal
319.2	319, All Cast	Ingot	5.5-6.5	0.6	3.0-4.0	0.10	0.10	. . .	0.10	0.10	0.20	. . .	. . .	0.20	bal
A319.0	. . .	S, P	5.5-6.5	1.0	3.0-4.0	0.50	0.10	. . .	0.35	3.0	0.25	. . .	. . .	0.50	bal
A319.1	. . .	Ingot	5.5-6.5	0.8	3.0-4.0	0.50	0.10	. . .	0.35	3.0	0.25	. . .	. . .	0.50	bal
B319.0	SAE 329	S, P	5.5-6.5	1.2	3.0-4.0	0.8	0.10-0.50	. . .	0.50	1.0	0.25	. . .	. . .	0.50	bal
B319.1	. . .	Ingot	5.5-6.5	0.9	3.0-4.0	0.8	0.15-0.50	. . .	0.50	1.0	0.25	. . .	. . .	0.50	bal

320.0	. . .	S, P	5.0-8.0	1.2	2.0-4.0	0.8	0.05-0.6	. . .	0.35	3.0	0.25	. . .	. . .	0.50	bal
320.1	. . .	Ingot	5.0-8.0	0.9	2.0-4.0	0.8	0.10-0.6	. . .	0.35	3.0	0.25	. . .	. . .	0.50	bal
332.0	F332.0, F132	P	8.5-10.5	1.2	2.0-4.0	0.50	0.50-1.5	. . .	0.50	1.0	0.25	. . .	. . .	0.50	bal
332.1	F332.1, F132	Ingot	8.5-10.5	0.9	2.0-4.0	0.50	0.6-1.5	. . .	0.50	1.0	0.25	. . .	. . .	0.50	bal
332.2	F332.2, F132	Ingot	8.5-10.0	0.6	2.0-4.0	0.10	0.9-1.3	. . .	0.10	0.10	0.20	. . .	. . .	0.30	bal
333.0	333	P	8.0-10.0	1.0	3.0-4.0	0.50	0.05-0.50	. . .	0.50	1.0	0.25	. . .	. . .	0.50	bal
333.1	333	Ingot	8.0-10.0	0.8	3.0-4.0	0.50	0.10-0.50	. . .	0.50	1.0	0.25	. . .	. . .	0.50	bal
A333.0	. . .	P	8.0-10.0	1.0	3.0-4.0	0.50	0.05-0.50	. . .	0.50	3.0	0.25	. . .	. . .	0.50	bal
A333.1	. . .	Ingot	8.0-10.0	0.8	3.0-4.0	0.50	0.10-0.50	. . .	0.50	3.0	0.25	. . .	. . .	0.50	bal
336.0	A332.0, A132	P	11.0-13.0	1.2	0.50-1.5	0.35	0.7-1.3	. . .	2.0-3.0	0.35	0.25	. . .	0.05	. . .	bal
336.1	A332.1, A132	Ingot	11.0-13.0	0.9	0.50-1.5	0.35	0.8-1.3	. . .	2.0-3.0	0.35	0.25	. . .	0.05	. . .	bal
336.2	A332.2, A132	Ingot	11.0-13.0	0.9	0.50-1.5	0.10	0.9-1.3	. . .	2.0-3.0	0.10	0.20	. . .	0.05	0.15	bal
339.0	Z332.0, Z132	P	11.0-13.0	1.2	1.5-3.0	0.50	0.50-1.5	. . .	0.50-1.5	1.0	0.25	. . .	. . .	0.50	bal

339.1	Z332.1, Z132	Ingot	11.0-13.0	0.9	1.5-3.0	0.50	0.6-1.5	. . .	0.50-1.5	1.0	0.25	. . .	. . .	0.50	bal
354.0	354	P	8.6-9.4	0.20	1.6-2.0	0.10	0.40-0.6	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
354.1	354	Ingot	8.6-9.4	0.15	1.6-2.0	0.10	0.45-0.6	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
355.0	355	S, P	4.5-5.5	0.6(k)	1.0-1.5	0.50(k)	0.40-0.6	0.25	. . .	0.35	0.25	. . .	0.05	0.15	bal
355.1	355	Ingot	4.5-5.5	0.50(k)	1.0-1.5	0.50(k)	0.45-0.6	0.25	. . .	0.35	0.25	. . .	0.05	0.15	bal
355.2	355	Ingot	4.5-5.5	0.14-0.25	1.0-1.5	0.05	0.50-0.6	. . .	. . .	0.05	0.20	. . .	0.05	0.15	bal
A355.0	. . .	S, P	4.5-5.5	0.09	1.0-1.5	0.05	0.45-0.6	. . .	. . .	0.05	0.04-0.20	. . .	0.05	0.15	bal
A355.2	. . .	Ingot	4.5-5.5	0.06	1.0-1.5	0.03	0.50-0.6	. . .	. . .	0.03	0.04-0.20	. . .	0.03	0.10	bal
C355.0	C355	S, P	4.5-5.5	0.20	1.0-1.5	0.10	0.40-0.6	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
C355.1	. . .	Ingot	4.5-5.5	0.15	1.0-1.5	0.10	0.45-0.6	. . .	. . .	0.10	020	. . .	0.05	0.15	bal
C355.2	C355	Ingot	4.5-5.5	0.13	1.0-1.5	0.05	0.50-0.6	. . .	. . .	0.05	0.20	. . .	0.05	0.15	bal
356.0	356	S, P	6.5-7.5	0.6(k)	0.25	0.35(k)	0.20-0.45	. . .	. . .	0.35	0.25	. . .	0.05	0.15	bal
356.1	356	Ingot	6.5-7.5	0.50(k)	0.25	0.35(k)	0.25-0.45	. . .	. . .	0.35	0.25	. . .	0.05	0.15	bal
356.2	356	Ingot	6.5-7.5	0.13-0.25	0.10	0.05	0.30-0.45	. . .	. . .	0.05	0.20	. . .	0.05	0.15	bal

A356.0	A356	S, P	6.5-7.5	0.20	0.20	0.10	0.25-0.45	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
A356.1	. . .	Ingot	6.5-7.5	0.15	0.20	0.10	0.30-0.45	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
A356.2	A356	Ingot	6.5-7.5	0.12	0.10	0.05	0.30-0.45	. . .	. . .	0.05	0.20	. . .	0.05	0.15	bal
B356.0	. . .	S, P	6.5-7.5	0.09	0.05	0.05	0.25-0.45	. . .	. . .	0.05	0.04-0.20	. . .	0.05	0.15	bal
B356.2	. . .	Ingot	6.5-7.5	0.06	0.03	0.03	0.30-0.45	. . .	. . .	0.03	0.04-0.20	. . .	0.03	0.10	bal
C356.0	. . .	S, P	6.5-7.5	0.07	0.05	0.05	0.25-0.45	. . .	. . .	0.05	0.04-0.20	. . .	0.05	0.15	bal
C356.2	. . .	Ingot	6.5-7.5	0.04	0.03	0.03	0.30-0.45	. . .	. . .	0.03	0.04-0.20	. . .	0.03	0.10	bal
F356.0	. . .	S, P	6.5-7.5	0.20	0.20	0.10	0.17-0.25	. . .	. . .	0.10	0.04-0.20	. . .	0.05	0.15	bal
F356.2	. . .	Ingot	6.5-7.5	0.12	0.10	0.05	0.17-0.25	. . .	. . .	0.05	0.04-0.20	. . .	0.05	0.15	bal
357.0	357	S, P	6.5-7.5	0.15	0.05	0.03	0.45-0.6	. . .	. . .	0.05	0.20	. . .	0.05	0.15	bal
357.1	357	Ingot	6.5-7.5	0.12	0.05	0.03	0.45-0.6	. . .	. . .	0.05	0.20	. . .	0.05	0.15	bal
A357.0	A357	S, P	6.5-7.5	0.20	0.20	0.10	0.40-0.7	. . .	. . .	0.10	0.04-0.20	. . .	0.05(l)	0.15	bal
A357.2	A357	Ingot	6.5-7.5	0.12	0.10	0.05	0.45-0.7	. . .	. . .	0.05	0.04-0.20	. . .	0.03(l)	0.10	bal
B357.0	. . .	S, P	6.5-7.5	0.09	0.05	0.05	0.40-0.6	. . .	. . .	0.05	0.04-0.20	. . .	0.05	0.15	bal

B357.2	. . .	Ingot	6.5-7.5	0.06	0.03	0.03	0.45-0.6	. . .	. . .	0.03	0.04-0.20	. . .	0.03	0.10	bal
C357.0	. . .	S, P	6.5-7.5	0.09	0.05	0.05	0.45-0.7	. . .	. . .	0.05	0.04-0.20	. . .	0.05(l)	0.15	bal
C357.2	. . .	Ingot	6.5-7.5	0.06	0.03	0.03	0.50-0.7	. . .	. . .	0.03	0.04-0.20	. . .	0.03(l)	0.10	bal
D357.0	. . .	S	6.5-7.5	0.20	. . .	0.10	0.55-0.6	. . .	. . .	. . .	0.10-0.20	. . .	0.05(l)	0.15	bal
358.0	B358.0, Tens-50	S, P	7.6-8.6	0.30	0.20	0.20	0.40-0.6	0.20	. . .	0.20	0.10-0.20	. . .	0.05(m)	0.15	bal
358.2	B358.2, Tens-50	Ingot	7.6-8.6	0.20	0.10	0.10	0.45-0.6	0.05	. . .	0.10	0.12-0.20	. . .	0.05(n)	0.15	bal
359.0	359	S, P	8.5-9.5	0.20	0.20	0.10	0.50-0.7	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
359.2	359	Ingot	8.5-9.5	0.12	0.10	0.10	0.55-0.7	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
A359.0	. . .	. . .	8.5-9.5	0.25	0.20	0.10	0.40-0.6	. . .	. . .	0.05	0.20	. . .	0.03	0.10	bal
A359.1	. . .	Ingot(j)	8.5-9.5	0.20	0.20	0.10	0.45-0.6	. . .	. . .	0.05	0.20	. . .	0.03	0.10	bal
360.0(o)	360	D	9.0-10.0	2.0	0.6	0.35	0.40-0.6	. . .	0.50	0.50	. . .	0.15	. . .	0.25	bal
360.2	360	Ingot	9.0-10.0	0.7-1.1	0.10	0.10	0.45-0.6	. . .	0.10	0.10	. . .	0.10	. . .	0.20	bal
A360.0(o)	A360	D	9.0-10.0	1.3	0.6	0.35	0.40-0.6	. . .	0.50	0.50	. . .	0.15	. . .	0.25	bal
A360.1(o)	A360	Ingot	9.0-10.0	1.0	0.6	0.35	0.45-0.6	. . .	0.50	0.40	. . .	0.15	. . .	0.25	bal

A360.2	A360	Ingot	9.0-10.0	0.6	0.10	0.05	0.45-0.6	. . .	. . .	0.05	. . .	. . .	0.05	0.15	bal
361.0	. . .	D	9.5-10.5	1.1	0.50	0.25	0.40-0.6	0.20-0.30	0.20-0.30	0.50	0.20	0.10	0.05	0.15	bal
361.1	. . .	Ingot	9.5-10.5	0.8	0.50	0.25	0.45-0.6	0.20-0.30	0.20-0.30	0.40	0.20	0.10	0.05	0.15	bal
363.0	363	S, P	4.5-6.0	1.1	2.5-3.5	(p)	0.15-0.40	(p)	0.25	3.0-4.5	0.20	0.25	(q)	0.30	bal
363.1	363	Ingot	4.5-6.0	0.8	2.5-3.5	(p)	0.20-0.40	(p)	0.25	3.0-4.5	0.20	0.25	(q)	0.30	bal
364.0	364	D	7.5-9.5	1.5	0.20	0.10	0.20-0.40	0.25-0.50	0.15	0.15	. . .	0.15	0.05(r)	0.15	bal
364.2	364	Ingot	7.5-9.5	0.7-1.1	0.20	0.10	0.25-0.40	0.25-0.50	0.15	0.15	. . .	0.15	0.05(r)	0.15	bal
369.0	Special K-9	D	11.0-12.0	1.3	0.50	0.35	0.25-0.45	0.30-0.40	0.05	1.0	. . .	0.10	0.05	0.15	bal
369.1	Special K-9	Ingot	11.0-12.0	1.0	0.50	0.35	0.30-0.45	0.30-0.40	0.05	0.9	. . .	0.10	0.05	0.15	bal
380.0(o)	380	D	7.5-9.5	2.0	3.0-4.0	0.50	0.10	. . .	0.50	3.0	. . .	0.35	. . .	0.50	bal
380.2	380	Ingot	7.5-9.5	0.7-1.1	3.0-4.0	0.10	0.10	. . .	0.10	0.10	. . .	0.10	. . .	0.20	bal
A380.0(o)	A380	D	7.5-9.5	1.3	3.0-4.0	0.50	0.10	. . .	0.50	3.0	. . .	0.35	. . .	0.50	bal

A380.1	A380	Ingot	7.5-9.5	1.0	3.0-4.0	0.50	0.10	. . .	0.50	2.9	. . .	0.35	. . .	0.50	bal
A380.2	A380	Ingot	7.5-9.5	0.6	3.0-4.0	0.10	0.10	. . .	0.10	0.10	. . .	. . .	0.05	0.15	bal
B380.0	A380	D	7.5-9.5	1.3	3.0-4.0	0.50	0.10	. . .	0.50	1.0	. . .	0.35	. . .	0.50	bal
B380.1	A380	Ingot	7.5-9.5	1.0	3.0-4.0	0.50	0.10	. . .	0.50	0.9	. . .	0.35	. . .	0.50	bal
C380.0	. . .	D	7.5-9.5	1.3	3.0-4.0	0.50	0.10-0.30	. . .	0.50	3.0	. . .	0.35	. . .	0.50	bal
C380.1	. . .	Ingot	7.5-9.5	1.0	3.0-4.0	0.50	0.15-0.30	. . .	0.50	2.9	. . .	0.35	. . .	0.50	bal
D380.0	. . .	D	7.5-9.5	1.3	3.0-4.0	0.50	0.10-0.30	. . .	0.50	1.0	. . .	0.35	. . .	0.50	bal
D380.1	. . .	Ingot	7.5-9.5	1.0	3.0-4.0	0.50	0.15-0.30	. . .	0.50	0.9	. . .	0.35	. . .	0.50	bal
383.0	. . .	D	9.5-11.5	1.3	2.0-3.0	0.50	0.10	. . .	0.30	3.0	. . .	0.15	. . .	0.50	bal
383.1	. . .	Ingot	9.5-11.5	1.0	2.0-3.0	0.50	0.10	. . .	0.30	2.9	. . .	0.15	. . .	0.50	bal
383.2	. . .	Ingot	9.5-11.5	0.6-1.0	2.0-3.0	0.10	0.10	. . .	0.10	0.10	. . .	0.10	. . .	0.20	bal
A383.0	. . .	D	9.5-11.5	1.3	2.0-3.0	0.50	0.10-0.30	. . .	0.30	3.0	. . .	0.15	. . .	0.50	bal
A383.1	. . .	Ingot	9.5-11.5	1.0	2.0-3.0	0.50	0.15-0.30	. . .	0.30	2.9	. . .	0.15	. . .	0.50	bal
384.0	384	D	10.5-12.0	1.3	3.0-4.5	0.50	0.10	. . .	0.50	3.0	. . .	0.35	. . .	0.50	bal

384.1	384	Ingot	10.5-12.0	1.0	3.0-4.5	0.50	0.10	. . .	0.50	2.9	. . .	0.35	. . .	0.50	bal
384.2	384	Ingot	10.5-12.0	0.6-1.0	3.0-4.5	0.10	0.10	. . .	0.10	0.10	. . .	0.10	. . .	0.20	bal
A384.0	384	D	10.5-12.0	1.3	3.0-4.5	0.50	0.10	. . .	0.50	1.0	. . .	0.35	. . .	0.50	bal
A384.1	384	Ingot	10.5-12.0	1.0	3.0-4.5	0.50	0.10	. . .	0.50	0.9	. . .	0.35	. . .	0.50	bal
B384.0	. . .	D	10.5-12.0	1.3	3.0-4.5	0.50	0.10-0.30	. . .	0.50	1.0	. . .	0.35	. . .	0.50	bal
B384.1	. . .	Ingot	10.5-12.0	1.0	3.0-4.5	0.50	0.15-0.30	. . .	0.50	0.9	. . .	0.35	. . .	0.50	bal
C384.0	. . .	D	10.5-12.0	1.3	3.0-4.5	0.50	0.10-0.30	. . .	0.50	3.0	. . .	0.35	. . .	0.50	bal
C384.1	. . .	Ingot	10.5-12.0	1.0	3.0-4.5	0.50	0.15-0.30	. . .	0.50	2.9	. . .	0.35	. . .	0.50	bal
385.0	B384.0, 384	D	11.0-13.0	2.0	2.0-4.0	0.50	0.30	. . .	0.50	3.0	. . .	0.30	. . .	0.50	bal
385.1	B384.1, 384	Ingot	11.0-13.0	1.1	2.0-4.0	0.50	0.30	. . .	0.50	2.9	. . .	0.30	. . .	0.50	bal
390.0	390	D	16.0-18.0	1.3	4.0-5.0	0.10	0.45-0.65(s)	. . .	. . .	0.10	0.20	. . .	0.10	0.20	bal

390.2	390	Ingot	16.0-18.0	0.6-1.0	4.0-5.0	0.10	0.50-0.65[s]	. . .	. . .	0.10	0.20	. . .	0.10	0.20	bal
A390.0	A390	S, P	16.0-18.0	0.50	4.0-5.0	0.10	0.45-0.65[s]	. . .	. . .	0.10	0.20	. . .	0.10	0.20	bal
A390.1	A390	Ingot	16.0-18.0	0.40	4.0-5.0	0.10	0.50-0.65[s]	. . .	. . .	0.10	0.20	. . .	0.10	0.20	bal
B390.0	. . .	D	16.0-18.0	1.3	4.0-5.0	0.50	0.45-0.65[s]	. . .	0.10	1.5	0.20	. . .	0.10	0.20	bal
B390.1	. . .	Ingot	16.0-18.0	1.0	4.0-5.0	0.50	0.50-0.65[s]	. . .	0.10	1.4	0.20	. . .	0.10	0.20	bal
392.0	392	D	18.0-20.0	1.5	0.40-0.8	0.20-0.6	0.8-1.2	. . .	0.50	0.50	0.20	0.30	0.15	0.50	bal
392.1	392	Ingot	18.0-20.0	1.1	0.40-0.8	0.20-0.6	0.9-1.2	. . .	0.50	0.40	0.20	0.30	0.15	0.50	bal
393.0	Vanasil	S, P, D	21.0-23.0	1.3	0.7-1.1	0.10	0.7-1.3	. . .	2.0-2.5	0.10	0.10-0.20	. . .	0.05[t]	0.15	bal
393.1	Vanasil	Ingot	21.0-23.0	1.0	0.7-1.1	0.10	0.8-1.3	. . .	2.0-2.5	0.10	0.10-0.20	. . .	0.05[t]	0.15	bal
393.2	Vanasil	Ingot	21.0-23.0	0.8	0.7-1.1	0.10	0.8-1.3	. . .	2.0-2.5	0.10	0.10-0.20	. . .	0.05[t]	0.15	bal
408.2[u]	. . .	Ingot	8.5-9.5	0.6-1.3	0.10	0.10	. . .	. . .	. . .	0.10	. . .	. . .	0.10	0.20	bal

409.2(u)	. . .	Ingot	9.0-10.0	0.6-1.3	0.10	0.10	. . .	. . .	. . .	0.10	. . .	. . .	0.10	0.20	bal
411.2(u)	. . .	Ingot	10.0-12.0	0.6-1.3	0.20	0.10	. . .	. . .	. . .	0.10	. . .	. . .	0.10	0.20	bal
413.0(o)	13	D	11.0-13.0	2.0	1.0	0.35	0.10	. . .	0.50	0.50	. . .	0.15	. . .	0.25	bal
413.2	13	Ingot	11.0-13.0	0.7-1.1	0.10	0.10	0.07	. . .	0.10	0.10	. . .	0.10	. . .	0.20	bal
A413.0(o)	A13	D	11.0-13.0	1.3	1.0	0.35	0.10	. . .	0.50	0.50	. . .	0.15	. . .	0.25	bal
A413.1(o)	A13	Ingot	11.0-13.0	1.0	1.0	0.35	0.10	. . .	0.50	0.40	. . .	0.15	. . .	0.25	bal
A413.2	A13	Ingot	11.0-13.0	0.6	0.10	0.05	0.05	. . .	0.05	0.05	. . .	0.05	. . .	0.10	bal
B413.0	. . .	S, P	11.0-13.0	0.50	0.10	0.35	0.05	. . .	0.05	0.10	0.25	. . .	0.05	0.20	bal
B413.1	. . .	Ingot	11.0-13.0	0.40	0.10	0.35	0.05	. . .	0.05	0.10	0.25	. . .	0.05	0.20	bal
435.2(v)	. . .	Ingot	3.3-3.9	0.40	0.05	0.05	0.05	. . .	. . .	0.10	. . .	. . .	0.05	0.20	bal
443.0	43	S, P	4.5-6.0	0.8	0.6	0.50	0.05	0.25	. . .	0.50	0.25	. . .	. . .	0.35	bal
443.1	43	Ingot	4.5-6.0	0.6	0.6	0.50	0.05	0.25	. . .	0.50	0.25	. . .	. . .	0.35	bal

443.2	43	Ingot	4.5-6.0	0.6	0.10	0.10	0.05	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
A443.0	43(0.30 max Cu)	S	4.5-6.0	0.8	0.30	0.50	0.05	0.25	. . .	0.50	0.25	. . .	. . .	0.35	bal
A443.1	43(0.30 max Cu)	Ingot	4.5-6.0	0.6	0.30	0.50	0.05	0.25	. . .	0.50	0.25	. . .	. . .	0.35	bal
B443.0	43(0.15 max Cu)	S, P	4.5-6.0	0.8	0.15	0.35	0.05	. . .	. . .	0.35	0.25	. . .	0.05	0.15	bal
B443.1	43(0.15 max Cu)	Ingot	4.5-6.0	0.6	0.15	0.35	0.05	. . .	. . .	0.35	0.25	. . .	0.05	0.15	bal
C443.0	A43	D	4.5-6.0	2.0	0.6	0.35	0.10	. . .	0.50	0.50	. . .	0.15	. . .	0.25	bal
C443.1	A43	Ingot	4.5-6.0	1.1	0.6	0.35	0.10	. . .	0.50	0.40	. . .	0.15	. . .	0.25	bal
C443.2	A43	Ingot	4.5-6.0	0.7-1.1	0.10	0.10	0.05	. . .	. . .	0.10	. . .	. . .	0.05	0.15	bal
444.0	. . .	S, P	6.5-7.5	0.6	0.25	0.35	0.10	. . .	. . .	0.35	0.25	. . .	0.05	0.15	bal
444.2	. . .	Ingot	6.5-7.5	0.13-0.25	0.10	0.05	0.05	. . .	. . .	0.05	0.20	. . .	0.05	0.15	bal
A444.0	A344	P	6.5-7.5	0.20	0.10	0.10	0.05	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
A444.1	. . .	Ingot	6.5-7.5	0.15	0.10	0.10	0.05	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
A444.2	A344	Ingot	6.5-7.5	0.12	0.05	0.05	0.05	. . .	. . .	0.05	0.20	. . .	0.05	0.15	bal
445.2(u)	B444.2	Ingot	6.5-7.5	0.6-1.3	0.10	0.10	. . .	. . .	. . .	0.10	. . .	. . .	0.10	0.20	bal

511.0	F514.0, F214	S	0.30-0.7	0.50	0.15	0.35	3.5-4.5	. . .	. . .	0.15	0.25	. . .	0.05	0.15	bal
511.1	F514.1, F214	Ingot	0.30-0.7	0.40	0.15	0.35	3.6-4.5	. . .	. . .	0.15	0.25	. . .	0.05	0.15	bal
511.2	F514.2, F214	Ingot	0.30-0.7	0.30	0.10	0.10	3.6-4.5	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
512.0	B514.0, B214	S	1.4-2.2	0.6	0.35	0.8	3.5-4.5	0.25	. . .	0.35	0.25	. . .	0.05	0.15	bal
512.2	B514.2, B214	Ingot	1.4-2.2	0.30	0.10	0.10	3.6-4.5	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
513.0	A514.0, A214	P	0.30	0.40	0.10	0.30	3.5-4.5	. . .	. . .	1.4-2.2	0.20	. . .	0.05	0.15	bal
513.2	A514.2, A214	Ingot	0.30	0.30	0.10	0.10	3.6-4.5	. . .	. . .	1.4-2.2	0.20	. . .	0.05	0.15	bal
514.0	214	S	0.35	0.50	0.15	0.35	3.5-4.5	. . .	. . .	0.15	0.25	. . .	0.05	0.15	bal
514.1	214	Ingot	0.35	0.40	0.15	0.35	3.6-4.5	. . .	. . .	0.15	0.25	. . .	0.05	0.15	bal
514.2	214	Ingot	0.30	0.30	0.10	0.10	3.6-4.5	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
515.0	L514.0, L214	D	0.50-1.0	1.3	0.20	0.40-0.6	2.5-4.0	. . .	. . .	0.10	. . .	. . .	0.05	0.15	bal
515.2	L514.2, L214	Ingot	0.50-1.0	0.6-1.0	0.10	0.40-0.6	2.7-4.0	. . .	. . .	0.05	. . .	. . .	0.05	0.15	bal
516.0	. . .	D	0.30-1.5	0.35-1.0	0.30	0.15-0.40	2.5-4.5	. . .	0.25-0.40	0.20	0.10-0.20	0.10	0.05(w)	. . .	bal
516.1	. . .	Ingot	0.30-1.5	0.35-0.7	0.30	0.15-	2.6-4.5	. . .	0.25-	0.20	0.10-0.20	0.10	0.05(w)	. . .	bal

						0.40			0.40						
518.0	218	D	0.35	1.8	0.25	0.35	7.5-8.5	. . .	0.15	0.15	. . .	0.15	. . .	0.25	bal
518.1	218	Ingot	0.35	1.1	0.25	0.35	7.6-8.5	. . .	0.15	0.15	. . .	0.15	. . .	0.25	bal
518.2	218	Ingot	0.25	0.7	0.10	0.10	7.6-8.5	. . .	0.05	. . .	. . .	0.05	. . .	0.10	bal
520.0	220	S	0.25	0.30	0.25	0.15	9.5-10.6	. . .	. . .	0.15	0.25	. . .	0.05	0.15	bal
520.2	220	Ingot	0.15	0.20	0.20	0.10	9.6-10.6	. . .	. . .	0.10	0.20	. . .	0.05	0.15	bal
535.0	Almag 35	S	0.15	0.15	0.05	0.10-0.25	6.2-7.5	. . .	. . .	. . .	0.10-0.25	. . .	0.05(x)	0.15	bal
535.2	Almag 35	Ingot	0.10	0.10	0.05	0.10-0.25	6.6-7.5	. . .	. . .	. . .	0.10-0.25	. . .	0.05(y)	0.15	bal
A535.0	A218	S	0.20	0.20	0.10	0.10-0.25	6.5-7.5	. . .	. . .	. . .	0.25	. . .	0.05	0.15	bal
A535.1	A218	Ingot	0.20	0.15	0.10	0.10-0.25	6.6-7.5	. . .	. . .	. . .	0.25	. . .	0.05	0.15	bal
B535.0	B218	S	0.15	0.15	0.10	0.05	6.5-7.5	. . .	. . .	. . .	0.10-0.25	. . .	0.05	0.15	bal
B535.2	B218	Ingot	0.10	0.12	0.05	0.05	6.6-7.5	. . .	. . .	. . .	0.10-0.25	. . .	0.05	0.15	bal
705.0	603, Ternalloy 5	S, P	0.20	0.8	0.20	0.40-0.6	1.4-1.8	0.20-0.40	. . .	2.7-3.3	0.25	. . .	0.05	0.15	bal

705.1	603, Ternalloy 5	Ingot	0.20	0.6	0.20	0.40-0.6	1.5-1.8	0.20-0.40	. . .	2.7-3.3	0.25	. . .	0.05	0.15	bal
707.0	607, Ternalloy 7	S, P	0.20	0.8	0.20	0.40-0.6	1.8-2.4	0.20-0.40	. . .	4.0-4.5	0.25	. . .	0.05	0.15	bal
707.1	607, Ternalloy 7	Ingot	0.20	0.6	0.20	0.40-0.6	1.9-2.4	0.20-0.40	. . .	4.0-4.5	0.25	. . .	0.05	0.15	bal
710.0	A712.0, A612	S	0.15	0.50	0.35-0.6	0.05	0.6-0.8	. . .	. . .	6.0-7.0	0.25	. . .	0.05	0.15	bal
710.1	A712.1, A612	Ingot	0.15	0.40	0.35-0.6	0.05	0.65-0.8	. . .	. . .	6.0-7.0	0.25	. . .	0.05	0.15	bal
711.0	C712.0, C612	P	0.30	0.7-1.4	0.35-0.6	0.05	0.25-0.45	. . .	. . .	6.0-7.0	0.20	. . .	0.05	0.15	bal
711.1	C712.1, C612	Ingot	0.30	0.7-1.1	0.35-0.6	0.05	0.30-0.45	. . .	. . .	6.0-7.0	0.20	. . .	0.05	0.15	bal
712.0	D712.0, D612, 40E	S	0.30	0.50	0.25	0.10	0.50-0.65(s)	0.40-0.6	. . .	5.0-6.5	0.15-0.25	. . .	0.05	0.20	bal
712.2	D712.2, D612, 40E	Ingot	0.15	0.40	0.25	0.10	0.50-0.65(s)	0.40-0.6	. . .	5.0-6.5	0.15-0.25	. . .	0.05	0.20	bal
713.0	613, Tenzaloy	S, P	0.25	1.1	0.40-1.0	0.6	0.20-0.50	0.35	0.15	7.0-8.0	0.25	. . .	0.10	0.25	bal
713.1	613, Tenzaloy	Ingot	0.25	0.8	0.40-1.0	0.6	0.25-0.50	0.35	0.15	7.0-8.0	0.25	. . .	0.10	0.25	bal

771.0	Precedent 71A	S	0.15	0.15	0.10	0.10	0.8-1.0	0.06-0.20	. . .	6.5-7.5	0.10-0.20	. . .	0.05	0.15	bal
771.2	Precedent 71A	Ingot	0.10	0.10	0.10	0.10	0.85-1.0	0.06-0.20	. . .	6.5-7.5	0.10-0.20	. . .	0.05	0.15	bal
772.0	B771.0, Precedent 71B	S	0.15	0.15	0.10	0.10	0.6-0.8	0.06-0.20	. . .	6.0-7.0	0.10-0.20	. . .	0.05	0.15	bal
772.2	B771.2, Precedent 71B	Ingot	0.10	0.10	0.10	0.10	0.65-0.8	0.06-0.20	. . .	6.0-7.0	0.10-0.20	. . .	0.05	0.15	bal
850.0	750	S, P	0.7	0.7	0.7-1.3	0.10	0.10	. . .	0.7-1.3	. . .	0.20	5.5-7.0	. . .	0.30	bal
850.1	750	Ingot	0.7	0.50	0.7-1.3	0.10	0.10	. . .	0.7-1.3	. . .	0.20	5.5-7.0	. . .	0.30	bal
851.0	A850.0, A750	S, P	2.0-3.0	0.7	0.7-1.3	0.10	0.10	. . .	0.30-0.7	. . .	0.20	5.5-7.0	. . .	0.30	bal
851.1	A850.1, A750	Ingot	2.0-3.0	0.50	0.7-1.3	0.10	0.10	. . .	0.30-0.7	. . .	0.20	5.5-7.0	. . .	0.30	bal
852.0	B850.0, B750	S, P	0.40	0.7	1.7-2.3	0.10	0.6-0.9	. . .	0.9-1.5	. . .	0.20	5.5-7.0	. . .	0.30	bal
852.1	B850.1, B750	Ingot	0.40	0.50	1.7-2.3	0.10	0.7-0.9	. . .	0.9-1.5	. . .	0.20	5.5-7.0	. . .	0.30	bal
853.0	XC850.0, XC750	S, P	5.5-6.5	0.7	3.0-4.0	0.50	. . .	. . .	. . .	. . .	0.20	5.5-7.0	. . .	0.30	bal

853.2	XC850.2, XC750	Ingot	5.5-6.5	0.50	3.0-4.0	0.10	. . .	. . .	. . .	. . .	0.20	5.5-7.0	. . .	0.30	bal

Source: Aluminum Association Inc.

(a) D, die casting. P, permanent mold. S, sand. Other products may pertain to the composition shown even though not listed.

(b) 0.025% max Mg +Cr + Ti + V.

(c) Fe/Si ratio 2.5 min.

(d) Fe/Si ratio 2.0 min.

(e) Fe/Si ratio 1.5 min.

(f) 0.40-1.0% Ag.

(g) 0.50-1.0% Ag.

(h) 0.50% max Ti + Zr.

(i) 0.20-0.30%Sb, 0.20-0.30% Co, 0.10-0.30% Zr.

(j) Primarily used for making metal-matrix composite.

(k) If Fe exceeds 0.45%, Mg content will not be less than one-half Fe content.

(l) 0.04-0.07% Be.

(m) 0.10-0.30%Be.

(n) 0.15-0.30% Be.

(o) A360.1, A380.1, and A413.1 ingot is used to produce 360.0 and A360.0; 380.0 and A380.0; 413.0 and A413.0 castings, respectively.

(p) 0.8% max Mg +Cr.

(q) 0.25% max Pb.

(r) 0.02-0.04% Be.

(s) The number of decimal places to which Mg percent is expressed differs from the norm.

(t) 0.08-0.15%V.

(u) 408.2, 409.2, 411.2, and 445.2 are used to coat steel.

(v) Used with Zn to coat steel.

(w) 0.10% max Pb.

(x) 0.003-0.007%Be, 0.005% max B.

(y) 0.003-0.007%Be, 0.002 max B.

Chemical Compositions and International Designations for Aluminum Alloys

Cross Referencing Aluminum Alloy Designations

Unified Numbering System (UNS)

The UNS numbers correlate many nationally used numbering systems currently administered by societies, trade associations, and individual users and producers of metals and alloys. Table 3cross references AA (Aluminum Association) numbers to UNS numbers.

Table 3 Unified Numbering System (UNS) numbers corresponding to Aluminum Association(AA) numbers for aluminum and aluminum alloys

AA No.	UNS No.
Castings/ingot	
100.1	A01001
130.1	A01301
150.1	A01501
160.1	A01601
170.1	A01701
201.0	A02010
201.2	A02012
202.0	A02020
202.2	A02022
203.0	A02030
203.2	A02032

204.0	A02040
204.2	A02042
206.0	A02060
206.2	A02062
208.0	A02080
208.1	A02081
208.2	A02082
213.0	A02130
213.1	A02131
222.0	A02220
222.1	A02221
224.0	A02240
224.2	A02242
238.0	A02380
238.1	A02381
238.2	A02382
240.0	A02400
240.1	A02401
242.0	A02420
242.1	A02421
242.2	A02422

243.0	A02430
243.1	A02431
249.0	A02490
249.2	A02492
295.0	A02950
295.1	A02951
295.2	A02952
296.0	A02960
296.1	A02961
296.2	A02962
305.0	A03050
305.2	A03052
308.0	A03080
308.1	A03081
308.2	A03082
318.0	A03180
318.1	A03181
319.0	A03190
319.1	A03191
319.2	A03192
320.0	A03200

320.1	A03201
324.0	A03240
324.1	A03241
324.2	A03242
328.0	A03280
328.1	A03281
332.0	A03320
332.1	A03321
332.2	A03322
333.0	A03330
333.1	A03331
336.0	A03360
336.1	A03361
336.2	A03362
339.0	A03390
339.1	A03391
343.0	A03430
343.1	A03431
354.0	A03540
354.1	A03541
355.0	A03550

355.1	A03551
355.2	A03552
356.0	A03560
356.1	A03561
356.2	A03562
357.0	A03570
357.1	A03571
358.0	A03580
358.2	A03582
359.0	A03590
359.2	A03592
360.0	A03600
360.2	A03602
361.0	A03610
361.1	A03611
363.0	A03630
363.1	A03631
364.0	A03640
364.2	A03642
369.0	A03690
369.1	A03691

380.0	A03800
380.2	A03802
383.0	A03830
383.1	A03831
383.2	A03832
384.0	A03840
384.1	A03841
384.2	A03842
385.0	A03850
385.1	A03851
390.0	A03900
390.2	A03902
392.0	A03920
392.1	A03921
393.0	A03930
393.1	A03931
393.2	A03932
408.2	A04082
409.2	A04092
411.2	A04112
413.0	A04130

413.2	A04132
435.2	A04352
443.0	A04430
443.1	A04431
443.2	A04432
444.0	A04440
444.2	A04442
445.2	A04452
511.0	A05110
511.1	A05111
511.2	A05112
512.0	A05120
512.2	A05122
513.0	A05130
513.2	A05132
514.0	A05140
514.1	A05141
514.2	A05142
515.0	A05150
515.2	A05152
516.0	A05160

516.1	A05161
518.0	A05180
518.1	A05181
518.2	A05182
520.0	A05200
520.2	A05202
535.0	A05350
535.2	A05352
705.0	A07050
705.1	A07051
707.0	A07070
707.1	A07071
710.0	A07100
710.1	A07101
711.0	A07110
711.1	A07111
712.0	A07120
712.2	A07122
713.0	A07130
713.1	A07131
771.0	A07710

771.2	A07712
772.0	A07720
772.2	A07722
850.0	A08500
850.1	A08501
851.0	A08510
851.1	A08511
852.0	A08520
852.1	A08521
853.0	A08530
853.2	A08532
A201.0	A12010
A201.1	A12011
A201.2	A12012
A206.0	A12060
A206.2	A12062
A242.0	A12420
A242.1	A12421
A242.2	A12422
A305.0	A13050
A305.1	A13051

A305.2	A13052
A319.0	A13190
A319.1	A13191
A333.0	A13330
A333.1	A13331
A355.0	A13550
A355.2	A13552
A356.0	A13560
A356.2	A13562
A356.1	A13561
A357.0	A13570
A357.2	A13572
A360.0	A13600
A360.1	A13601
A360.2	A13602
A380.0	A13800
A380.1	A13801
A380.2	A13802
A383.0	A13830
A383.1	A13831
A384.0	A13840

A384.1	A13841
A390.0	A13900
A390.1	A13901
A413.0	A14130
A413.1	A14131
A413.2	A14132
A443.0	A14430
A443.1	A14431
A444.0	A14440
A444.2	A14442
A444.1	A14441
A535.0	A15350
A535.1	A15351
B201.0	A22010
B237.0	A23570
B319.0	A23190
B319.1	A23191
B356.0	A23560
B356.2	A23562
B357.2	A23572
B380.0	A23800

B380.1	A23801
B384.1	A23841
B390.0	A23900
B390.1	A23901
B413.0	A24130
B413.1	A24131
B443.0	A24430
B443.1	A24431
B535.0	A25350
B535.2	A25352
C355.0	A33550
C355.2	A35522
C355.1	A33551
C356.0	A33560
C356.2	A33562
C357.0	A33570
C357.2	A33572
C380.0	A33800
C380.1	A33801
C384.0	A33840
C384.1	A33841

C443.0	A34430
C443.1	A34431
C443.2	A34432
D357.0	A43570
D380.0	A43800
D380.1	A43801
F356.0	A63560
F356.2	A63562
Wrought alloys	
1030	A91030
1035	A91035
1040	A91040
1045	A91045
1050	A91050
1055	A91055
1060	A91060
1065	A91065
1070	A91070
1075	A91075
1080	A91080
1085	A91085

1090	A91090
1095	A91095
1098	A91098
1100	A91100
1110	A91110
1120	A91120
1135	A91135
1145	A91145
1150	A91150
1170	A91170
1175	A91175
1180	A91180
1185	A91185
1188	A91188
1190	A91190
1193	A91193
1198	A91198
1199	A91199
1200	A91200
1230	A91230
1235	A91235

1250	A91250
1260	A91260
1275	A91275
1285	A91285
1345	A91345
1350	A91350
1370	A91370
1385	A91385
1435	A91435
1445	A91445
1450	A91450
2001	A92001
2002	A92002
2003	A92003
2004	A92004
2005	A92005
2006	A92006
2007	A92007
2008	A92008
2009	A92009
2010	A92010

2011	A92011
2014	A92014
2017	A92017
2018	A92018
2020	A92020
2021	A92021
2024	A92024
2025	A92025
2030	A92030
2031	A92031
2036	A92036
2037	A92037
2038	A92038
2048	A92048
2090	A92090
2091	A92091
2117	A92117
2124	A92124
2214	A92214
2218	A92218
2219	A92219

2224	A92224
2304	A92034
2319	A92319
2324	A92324
2419	A92419
2519	A92519
2618	A92618
3002	A93002
3003	A93003
3004	A93004
3005	A93005
3006	A93006
3007	A93007
3008	A93008
3009	A93009
3010	A93010
3011	A93011
3012	A93012
3013	A93013
3014	A93014
3015	A93015

3016	A93016
3017	A93017
3102	A93102
3103	A93103
3104	A93104
3105	A93105
3107	A93107
3203	A93203
3204	A93204
3207	A93207
3303	A93303
3307	A93307
4002	A94002
4004	A94004
4006	A94006
4007	A94007
4008	A94008
4009	A94009
4010	A94010
4011	A94011
4013	A94013

4014	A94014
4015	A94015
4032	A94032
4043	A94043
4044	A94044
4045	A94045
4046	A94046
4047	A94047
4104	A94104
4145	A94145
4147	A94147
4343	A94343
4543	A94543
4643	A94643
5005	A95005
5006	A95006
5010	A95010
5013	A95013
5014	A95014
5016	A95016
5017	A95017

5034	A95034
5039	A95039
5040	A95040
5042	A95042
5043	A95043
5049	A95049
5050	A95050
5051	A95051
5052	A95052
5056	A95056
5058	A95058
5082	A95082
5083	A95083
5086	A95086
5087	A95087
5091	A95091
5110	A95110
5149	A95149
5150	A95150
5151	A95151
5154	A95154

5180	A95180
5182	A95182
5183	A95183
5205	A95205
5210	A95210
5249	A95249
5250	A95250
5251	A95251
5252	A95252
5254	A95254
5280	A95280
5283	A95283
5305	A95305
5310	A95310
5349	A95349
5351	A95351
5352	A95352
5356	A95356
5357	A95357
5451	A95451
5454	A95454

5456	A95456
5457	A95457
5505	A95505
5552	A95552
5554	A95554
5556	A95556
5557	A95557
5605	A95605
5652	A95652
5654	A95654
5657	A95657
5754	A95754
5854	A95854
6002	A96002
6003	A96003
6004	A96004
6005	A96005
6005A	A96005
6006	A96006
6007	A96007
6008	A96008

6009	A96009
6010	A96010
6011	A96011
6012	A96012
6013	A96013
6014	A96014
6015	A96015
6016	A96016
6017	A96017
6053	A96053
6056	A96056
6060	A96060
6061	A96061
6063	A96063
6066	A96066
6070	A96070
6081	A96081
6082	A96082
6090	A96090
6091	A96091
6092	A96092

6101	A96101
6103	A96103
6105	A96105
6106	A96106
6110	A96110
6111	A96111
6113	A96113
6151	A96151
6162	A96162
6181	A96181
6201	A96201
6205	A96205
6206	A96206
6253	A96253
6261	A96261
6262	A96262
6301	A96301
6306	A96306
6351	A96351
6401	A96401
6463	A96463

6763	A96763
6863	A96863
6951	A96951
7001	A97001
7003	A97003
7004	A97004
7005	A97005
7008	A97008
7009	A97009
7010	A97010
7011	A97011
7012	A97012
7013	A97013
7014	A97014
7015	A97015
7016	A97016
7017	A97017
7018	A97018
7019	A97019
7020	A97020
7021	A97021

7022	A97022
7023	A97023
7024	A97024
7025	A97025
7026	A97026
7027	A97027
7028	A97028
7029	A97029
7030	A97030
7031	A97031
7039	A97039
7046	A97046
7049	A97049
7050	A97050
7051	A97051
7055	A97055
7060	A97060
7064	A97064
7070	A97070
7072	A97072
7075	A97075

7076	A97076
7079	A97079
7090	A97090
7091	A97091
7104	A97104
7108	A97108
7109	A97109
7116	A97116
7129	A97129
7146	A97146
7149	A97149
7150	A97150
7175	A97175
7178	A97178
7179	A97179
7229	A97229
7277	A97277
7278	A97278
7472	A97472
7475	A97475
8001	A98001

8004	A98004
8005	A98005
8006	A98006
8007	A98007
8008	A98008
8009	A98009
8010	A98010
8013	A98013
8014	A98014
8015	A98015
8016	A98016
8017	A98017
8018	A98018
8020	A98020
8021	A98021
8022	A98022
8030	A98030
8040	A98040
8050	A98050
8076	A98076
8077	A98077

8079	A98079
8081	A98081
8090	A98090
8091	A98091
8111	A98111
8112	A98112
8130	A98130
8176	A98176
8177	A98177
8211	A98211
8276	A98276
8280	A98280

International Alloy Designations

Historically, all major industrialized countries developed their own standard designations for aluminum and aluminum alloys. These are now being grouped under systems of the American National Standards Institute (ANSI), the International Organization for Standardization (ISO), and the European Committee for Standardization (Comité de Normalization, CEN).

The International Organization for Standardization has developed its own alphanumeric designation system for wrought aluminum and its alloys (ISO R209) based on the systems that have been used by certain European countries. The main addition element is distinguished by specifying the required content (middle of range) rounded off to the nearest 0.5:

5052 = Al Mg2.5
5251 = Al Mg2

If required, the secondary addition elements are distinguished by specifying the required content rounded off to the nearest 0.1, for two elements at most:

6181 = Al Si1Mg0.8

The chemical symbols for addition elements should be limited to four:

7050 = Al Zn6CuMgZr

If an alloy cannot otherwise be distinguished, a suffix in parentheses is used:

6063 = Al Mg0.7Si
6463= Al Mg0.7Si(B)
6063A = Al Mg0.7Si(A)

Note that suffixes (A),(B), and so on should not be confused with suffixes of the Aluminum Association.

Table 4 cross references ISO designations with equivalent or similar AA alloy designations. Also included in this table are cross-referenced alloys listed in Austrian, Canadian, French, German, British, Italian, Spanish, and Swiss standards. Additional information is included in the "Registration Record of International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys" (commonly referred to as the blue sheets) published by the Aluminum Association.

Table 4 International alloy designations cross referenced to wrought Aluminum Association (AA) alloys

The table includes only those alloys that are essentially equivalent in composition to the corresponding AA alloys, but whose composition limits are not necessarily exactly the same as their AA counterparts.

International alloy designation	Equivalent/similar AA alloy
ISO R209	
Al 99.5	1050A
Al 99.6	1060
Al 99.7	1070A
Al 99.8	1080A
Al 99.0 Cu	1100
Al 99.0	1200
Al 99.3	1230
E-Al 99.5	1350
E-Al 99.7	1370
Al Cu6BiPb	2011
Al Cu4SiMg	2014

Al Cu4SiMg(A)	2014A
Al Cu4MgSi	2017
Al Cu4MgSi(A)	2017A
Al Cu4Mg1	2024
Al Cu4PbMg	2030
Al Cu2.5Mg	2117
Al Cu6Mn	2219
Al Mn1Cu	3003
Al Mn1Mg1	3004
Al Mn1Mg0.5	3005
Al Mn1	3103
Al Mn0.5Mg0.5	3105
Al Si5	4043
Al Si5(A)	4043A
Al Si12	4047
Al Si12(A)	4047A
Al Mg1(B)	5005
Al Mg1.5(C)	5050
Al Mg2.5	5052
Al Mg5Cr	5056
Al Mg5	5056A

Al Mg4.5Mn0.7	5083
Al Mg4	5086
Al Mg3.5	5154
Al Mg3.5(A)	5154A
Al Mg4.5Mn0.7(A)	5183
Al Mg2	5251
Al Mg5Cr(A)	5356
Al Mg3Mn	5454
Al Mg5Mn	5456
Al Mg3Mn(A)	5554
Al Mg3	5754
Al SiMg	6005
Al SiMg(A)	6005A
Al MgSi	6060
Al Mg1SiCu	6061
Al Mg0.7Si	6063
Al Mg0.7Si(A)	6063A
Al Si1MgMn	6082
E-Al MgSi	6101
E-Al MgSi(A)	6101A
Al Si1Mg0.8	6181

Al Mg1SiPb	6262
Al Si1Mg0.5Mn	6351
Al Zn4.5Mg1.5Mn	7005
Al Zn6MgCu	7010
Al Zn4.5Mg1	7020
Al Zn8MgCu	7049A
Al Zn6CuMgZr	7050
Al Zn5.5MgCu	7075
Al Zn7MgCu	7178
Al Zn5.5MgCu(A)	7475
Austria (Austrian Standard M3430)	
A199	1200
A199.5	1050
E-Al	1350
AlCuMg1	2017
AlCuMg2	2024
AlCuMg0.5	2117
AlMg5	5056
AlMgSi0.5	6063
E-AlMgSi	6101
AlZnMgCu1.5	7075

Canada (Canadian Standards Association)	
990C	1100
CB60	2011
CG30	2117
CG42	2024
CG42 Alclad	Alclad 2024
CM41	2017
CN42	2018
CS41N	2014
CS41N Alclad	Alclad 2014
CS41P	2025
GM31N	5454
GM41	5083
GM50P	5356
GM50R	5056
GR20	5052
GS10	6063
GS11N	6061
GS11P	6053
MC10	3003
S5	4043

SG11P	6151
SG121	4032
ZG62	7075
ZG62 Alclad	Alclad 7075
France (Normes Francaises)	
A5/L	1350
A45	1100
A-G1	5050
A-G0.6	5005
A-G4MC	5086
A-GS	6063
A-GS/L	6101
A-M1	3003
A-M1G	3004
A-U4G	2017
A-U2G	2117
A-U2GN	2618
A-U4G1	2024
A-U4N	2218
A-U4SG	2014
A-S12UN	4032

A-Z5GU	7075
Germany (Deutsche Industrie-Norm.)	
E-A1995	1350
AlCuBiPb	2011
AlCuMg0.5	2117
AlCuMg1	2017
AlCuMg2	2024
AlCuSiMn	2014
AlMg4.5Mn	5083
AlMgSi0.5	6063
AlSi5	4043
E-AlMgSi0.5	6101
AlZnMgCu1.5	7075
Germany (Werkstoff-Nr.)	
3.0257	1350
3.1655	2011
3.1305	2117
3.1325	2017
3.1355	2024
3.1255	2014
3.3547	5083

3.3206	6063
3.2245	4043
3.3207	6101
3.4365	7075
Great Britain (British Standard)	
1E	1350
91E	6101
H14	2017
H19	6063
H20	6061
L.80, L.81	5052
L.86	2117
L.87	2017
L.93, L.94	2014A
L.95, L.96	7075
L.97, L.98	2024
2L.55, 2L.56	5052
2L.58	5056
3L.44	5050
5L.37	2017
6L.25	2218

N8	5083
N21	4043
Great Britain (Directorate of Technical Development)	
150A	2017
324A	4032
372B	6063
717, 724, 731A	6063
745, 5014, 5084	2618
5090	2024
5100	Alclad 2024
Italy (Unificazione Nazionale Italiana)	
P-AlCu4MgMn	2017
P-AlCu4.5MgMn	2024
P-AlCu4.5MgMnplacc.	Alclad 2024
P-AlCu2.5MgSi	2117
P-AlCu4.4SiMnMg	2014
P-AlCu4.4SiMnMgplacc.	Alclad 2014
P-AlMg0.9	5657
P-AlMg1.5	5050
P-AlMg2.5	5052
P-AlSi0.4Mg	6063

P-AlSi0.5Mg	6101
Spain (Una Norma Espanol)	
A199.5E	1350
L-313	2014
L-314	2024
L-315	2218
L-371	7075
Switzerland (Verein Schweizerischer Maschinenindustrieller)	
Al-Mg-Si	6101
Al1.5Mg	5050
Al-Cu-Ni	2218
Al3.5Cu0.5Mg	2017
Al4Cu1.2Mg	2027
Al-Zn-Mg-Cu	7075
Al-Zn-Mg-Cu-pl	Alclad 7075

Physical Metallurgy of Aluminum Alloys

Introduction

THE PRINCIPAL CONCERNS in the physical metallurgy of aluminum alloys include the effects of composition, mechanical working, and/or heat treatment on mechanical and physical properties. In terms of properties, strength improvement is a major objective in the design of aluminum alloys because the low strength of pure aluminum limits its commercial usefulness. The two most common methods for increasing the strength of aluminum alloys follow:

- To disperse second-phase constituents or elements in solid solution and cold work the alloy (non-heat-treatable alloys)
- To dissolve the alloying elements into solid solution and precipitate them as coherent submicroscopic particles (heat-treatable or precipitation-hardening alloys)

The factors affecting these strengthening mechanisms are reviewed in the first half of this article. The use of phase diagrams to better understand the effects of solid-state thermal processing is discussed in the second half of this article.

Alloying and Strengthening Mechanisms

The predominant reason for alloying is to increase strength, hardness, and resistance to wear, creep, stress relaxation or fatigue. Effects on these properties are specific to the different alloying elements and combinations of them, and are related to their alloy phase diagrams and to the microstructures and substructures that they form as a result of solidification, thermomechanical history, heat treatment and/or cold working.

The tensile yield strength of super-purity aluminum in its annealed (softest) state is approximately 10 MPa (1.5 ksi), whereas those of some heat treated commercial high-strength alloys exceed 550 MPa (80 ksi). When the magnitude of this difference (an increase of over 5000%) is considered, this practical, everyday accomplishment, which is just one aspect of the physical metallurgy of aluminum, is truly remarkable. Higher strengths, up to a yield strength of 690 MPa (100 ksi) and over, may be readily produced, but the fracture toughness of such alloys does not meet levels considered essential for aircraft or other critical-structure applications.

The elements that are most commonly present in commercial alloys to provide increased strength--particularly when coupled with strain hardening by cold working or with heat treatment, or both--are copper, magnesium, manganese, silicon, and zinc (Fig. 1). These elements all have significant solid solubility in aluminum, and in all cases the solubility increases with increasing temperature (see Fig. 2).

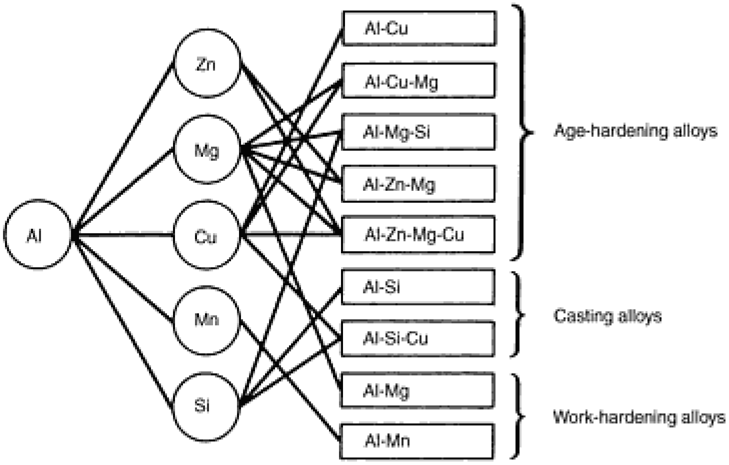


Fig. 1 The principal aluminum alloys

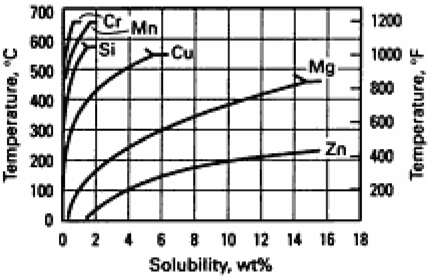


Fig. 2 Equilibrium binary solid solubility as a function of temperature for alloying elements most frequently added to aluminum

For those elements that form solid solutions, the strengthening effect when the element is in solution tends to increase with increasing difference in the atomic radii of the solvent (Al) and solute (alloying element) atoms. This factor is evident in data obtained from super-purity binary solid-solution alloys in the annealed state, presented in Table 1, but it is evident that other effects are involved, chief among which is an electronic bonding factor. The effects of multiple solutes in solid solution are somewhat less than additive and are nearly the same when one solute has a larger and the other a smaller atomic radius than that of aluminum as when both are either smaller or larger. Manganese in solid solution is highly effective in strengthening binary alloys. Its contribution to the strength of commercial alloys is less, because in these compositions, as a result of commercial mill fabricating operations, the manganese is largely precipitated.

Table 1 Solid-solution effects on strength of principal solute elements in super-purity aluminum

Element	Difference in atomic radii, $r_x - r_{Al}$, %(a)	Strength/addition values(b)							
		Yield strength/% addition(c)				**Tensile strength/% addition(d)**			
		MPa/at.%	**ksi/at.%**	**MPa/wt%**	**ksi/wt%**	**MPa/at.%**	**ksi/at.%**	**MPa/wt%**	**ksi/wt%**
Si	-3.8	9.3	1.35	9.2	1.33	40.0	5.8	39.6	5.75
Zn	-6.0	6.6	0.95	2.9	0.42	20.7	3.0	15.2	2.2
Cu	-10.7	16.2	2.35	13.8	2.0	88.3	12.8	43.1	6.25
Mn	-11.3	(e)	(e)	30.3	4.4	(e)	(e)	53.8	7.8

(a) Listed in order of increasing percent difference in atomic radii.

(b) Some property to percent addition relationships are nonlinear. Generally, the unit effects of smaller additions are greater.

(c) Increase in yield strength (0.2% offset) for 1% (atomic or weight basis) alloy addition.

(d) Increase in ultimate tensile strength for 1% (atomic or weight basis) alloy addition.

(e) 1 at.% of manganese is not soluble.

The principal alloys that are strengthened by alloying elements in solid solution (often coupled with cold work) are those in the aluminum-magnesium series, ranging form 0.5 to 6 wt% Mg. These alloys often contain small additions of transition elements, such as chromium or manganese, and less frequently zirconium, to control the grain or subgrain structure, and iron and silicon impurities that usually are present in the form of intermetallic particles. Figure 3 illustrates the effect of magnesium in solid solution on the yield strength and tensile elongation for most of the common aluminum-magnesium commercial alloys.

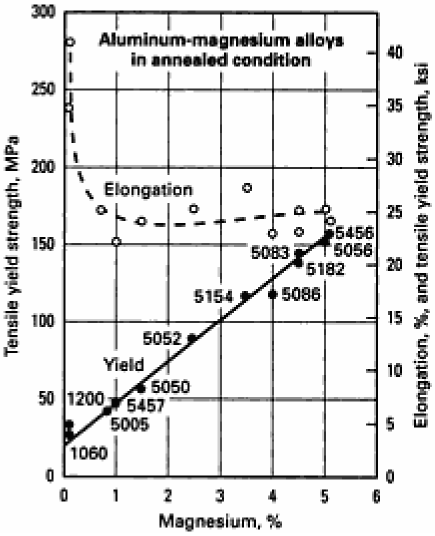


Fig. 3 Correlation between tensile yield, strength elongation, and magnesium content for some commercial aluminum alloys

Elements and combinations that form predominantly second-phase constituents with relatively low solid solubility include iron, nickel, titanium, manganese and chromium, and combinations thereof. The presence of increasing volume fractions of the intermetallic-compound phases formed by these elements and the elemental silicon constituent formed by silicon during solidification or by precipitation in the solid state during postsolidification heating also increases strength and hardness. The rates of increase per unit weight of alloying element added are frequently similar to but usually lower than those resulting form solid solution. This "second-phase" hardening occurs even though the constituent particles are of sizes readily resolved by optical microscopy. These irregularly shaped particles form during solidification and occur mostly along grain boundaries and between dendrite arms.

Manganese and chromium are included in the group of elements that form predominantly second phase constituents, because in commercial alloys they have very low equilibrium solid solubilities. In the case of many compositions containing manganese, this is because iron and silicon are also present and form the quaternary phase Al_{12} $(Fe,Mn)_3Si$. In alloys containing copper and manganese, the ternary phase $Al_{20}Cu_2Mn_3$ is formed. Most of the alloys in which chromium is present also contain magnesium, so that during solid-state heating they form $Al_{12}Mg_2Cr$, which also has very low equilibrium solid solubility. The concentrations of manganese and/or chromium held in solid solution in as-cast ingot that has been rapidly solidified and cooled from the molten state greatly exceed the equilibrium solubility. The solid solution is thus supersaturated and metastable. Ingot preheating for wrought commercial alloys containing these elements is designed to cause solid-state precipitation of the complex phase containing one or the other of these elements that is appropriate to the alloy composition. This precipitation does not cause appreciable hardening, nor is it intended that it should. Its purpose is to produce finely divided and dispersed particles that retard or inhibit recrystallization and grain growth in the alloy during subsequent heatings. The precipitate particles of $Al_{12}(Fe,Mn)_3Si$, $Al_{20}Cu_2Mn_3$, or $Al_{12}Mg_2Cr$

are incoherent with the matrix, and concurrent with their precipitation the original solid solution becomes less concentrated. These conditions do not provide appreciable precipitation hardening. Changes in electrical conductivity constitute an effective measure of the completeness of these precipitation reactions that occur in preheating.

For alloys that are composed of both solid-solution and second-phase constituents and/or dispersoid precipitates, all of these components of microstructure contribute to strength, in a roughly additive manner. This is shown in Fig. 4 for Al-Mg-Mn alloys in the annealed condition.

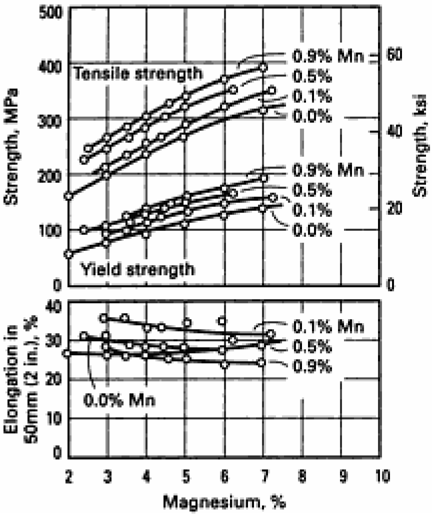


Fig. 4 Tensile properties in Al-Mg-Mn alloys in the form of annealed (O temper) plate 13 mm (0.5 in.) thick

Non-Heat-Treatable Alloys

By definition, the group of commercial alloys that are classed as non-heat-treatable are those that are not appreciably strengthened by heat treatment--that is, show no effective precipitation hardening. The strengthening mechanisms discussed so far (solid-solution formation, second-phase microstructural constituents and dispersoid precipitates) are those that provide the basis for the non-heat-treatable alloys. Wrought alloys of this type are mainly those of the 3*xxx* and 5*xxx* groups containing magnesium, manganese, and/or chromium, and the 1*xxx* aluminum group and some alloys of the 4*xxx* group that contain only silicon. Non-heat-treatable casting alloys are of the 4*xx.x* and 5*xx.x* groups, containing silicon or magnesium, respectively, and the 1*xx.x* aluminum group.

Strain Hardening. Strain hardening by cold rolling, drawing, or stretching is a highly effective means of increasing the strength of non-heat-treatable alloys. Work- or strain-hardening curves for several typical non-heat-treatable commercial alloys (Fig. 5) illustrate the increases in strength that accompany increasing reduction by cold rolling of initially annealed temper sheet. This increase is obtained at the expense of ductility as measured by percent elongation in a tensile test and by reduced formability in operations such as bending and drawing. It is frequently advantageous to employ material in a partially annealed (H2*x*) or stabilized (H3*x*) temper when bending, forming, or drawing is required, since materials in these tempers has greater forming capability for the same strength levels than does strain-hardened-only (H1*x*) material (see Table 2 for example).

Table 2 Tensile-property data illustrating typical relationship between strength and elongation for non-heat-treatable alloys in H1*x* versus H2*x* tempers

Alloy and temper	Tensile strength		Yield strength		Elongation, %
	MPa	**ksi**	**MPa**	**ksi**	

3105-H14	172	25	152	22	5
3105-H25	179	26	159	23	8
3105-H16	193	28	172	25	4

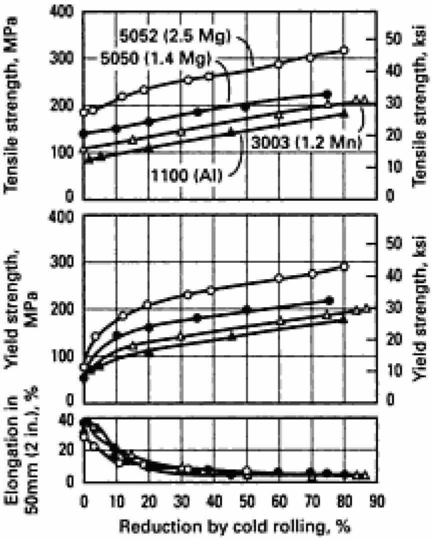


Fig. 5 Strain-hardening curves for aluminum (1100), Al-Mn (3003) alloys, and Al-Mg (5050 and 5052) alloys

All mill products can be supplied in the strain-hardened condition although there are limitations on the amounts of strain that can be applied to products such as die forgings and impacts. Even aluminum castings have been strengthened by cold pressing for certain applications.

Heat-Treatable Alloys and Precipitation Hardening

Again by definition, heat-treatable alloys are those that can be strengthened by suitable thermal treatment and include compositions used for wrought products as well as alloys for producing castings. Temperature-dependent solid solubility of the type shown for individual solutes in Fig. 1, the solubility increasing with increasing temperature, is a prerequisite. However, this feature alone does not make an alloy capable of precipitation hardening (or heat-treatable). The strengths of most binary alloys containing Mg, Si, Zn, Cr, or Mn alone exhibit little change from thermal treatments regardless of whether the solute is completely in solid solution, partially precipitated, or completed precipitated.

In contrast, alloys of the binary Al-Cu system having 3% Cu or more exhibit *natural aging* (hardening with time at ambient temperatures) after being solution heat treated and quenched. The amounts by which strength and hardness increase become larger with time of natural aging and with the copper content of the alloy from about 3% to the limit of solid solubility (5.65%). Natural aging curves for slowly quenched, high-purity Al-Cu alloys with 1 to 4.5% Cu are shown in Fig. 6. The rates and amounts of the changes in strength and hardness can be increased by holding the alloys at moderately elevated temperatures (for alloys of all types, the useful range is about 120 to 230 °C, or 250 to 450 °F). This treatment is called precipitation heat treating or *artificial aging.* In the Al-Cu system, alloys with as little as 1% Cu, again slowly quenched, start to harden after about 20 days at a temperature of 150 °C or 300 °F (see Fig. 7). The alloys of this system having less than ~3% Cu show little or no natural aging after low-cooling-rate quenching, which introduces little stress.

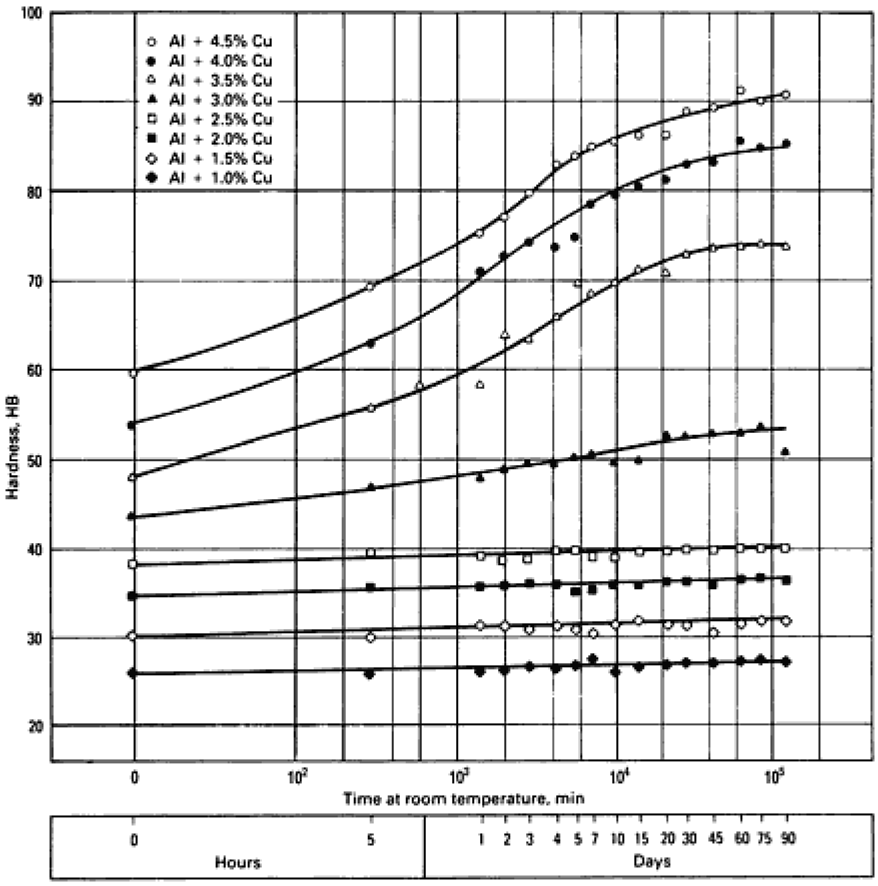


Fig. 6 Natural aging curves for binary Al-Cu alloys quenched in water at 100 °C (212 °F)

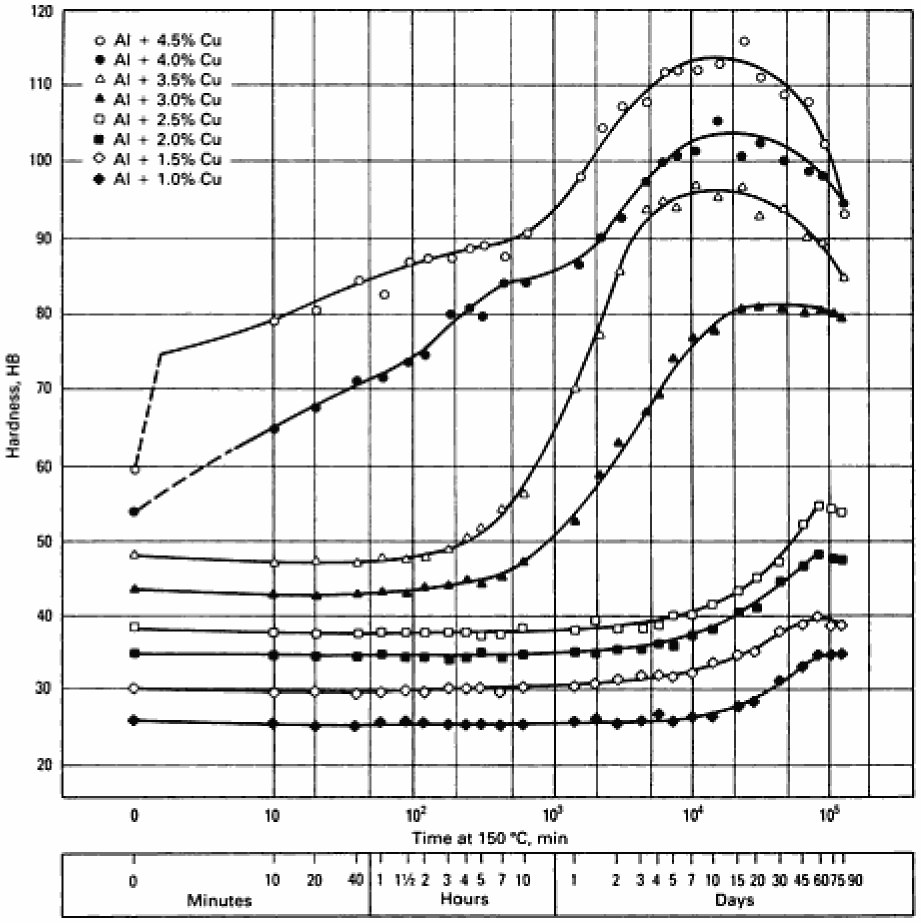


Fig. 7 Precipitation hardening curves for binary Al-Cu alloys quenched in water at 100 °C (212 °F) and aged at 150 °C (300 °F)

The characteristic that distinguishes between the systems having the required temperature to solid solubility relationship that does or does not exhibit precipitation hardening is the type or types of precipitate structures formed. Precipitation hardening is caused by a sequence of submicroscopic structure changes resulting from precipitation reactions that are responsible for the strength changes and can be revealed and analyzed only by such methods as x-ray diffraction and transmission electron microscopy. Room-temperature age hardening (natural aging) is a result of spontaneous formation of Guinier-Preston (G-P) zone structure. Solute atoms either cluster or segregate to selected atomic lattice planes, depending on the alloy system, to form the G-P zones, and this structure is more resistant to movement of dislocations through the lattice and, hence, is stronger.

Curves showing the changes in tensile yield strength with time at room temperature (natural aging curves) for three wrought commercial heat-treatable alloys of different alloy systems are shown in Fig. 8. The magnitudes of increase in this property are considerably different for the three alloys, and the differences in rate of change with time are of practical importance. Because 7075 and similar alloys never become completely stable under these conditions, they are rarely used in the naturally aged temper. On the other hand, 2024 is widely used in this condition.

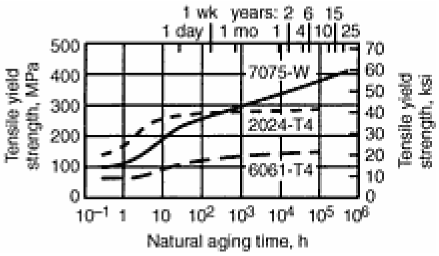


Fig. 8 Natural aging curves for three solution heat-treated wrought aluminum alloys

Precipitation heat treating (or artificial aging) at higher temperatures produces transition, metastable forms of the equilibrium precipitate of the of the particular alloy system. These transition precipitates are still coherent with the solid-solution matrix. The characteristic that determines whether a precipitate phase is coherent or noncoherent is the closeness of match or degree of disregistry between the atomic spacings on the lattice of the matrix and on that of the precipitate. The presence of the precipitate particles, and, even more importantly in most cases, the strain fields in the matrix surrounding the coherent particles, obstruct and retard the movement of dislocations, thus providing increased resistance to deformation--in other words, higher strength. These particles, at the maximum-strength stage, are extremely fine, are resolvable only by transmission electron microscopy (TEM), and constitute a relatively large volume fraction, particularly when the strain fields are considered.

With further heating at temperatures that cause strengthening or at higher temperatures, the precipitate particles grow, but even more importantly convert to the equilibrium phases, which generally are not coherent. These changes soften the material and, carried further, produce the softest or annealed condition. Even at this stage, the precipitate particles are still too small to be clearly resolved by optical microscopy, although etching effects are readily observed--particularly in alloys containing copper.

Precipitation heat treatment or artificial aging curves for the Al-Mg-Si wrought alloy 6061 are shown in Fig. 9. This is a typical family of curves showing the changes in tensile yield strength that accrue with increasing time at each of a series of temperatures. In all cases, the material has been given a solution heat treatment followed by a quench just prior to the start of the precipitation heat treatment. For detailed presentation of heat treating operations, parameters, and practices see the Section "Heat Treating" in this Handbook.

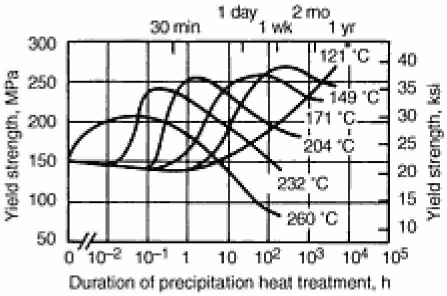


Fig. 9 Precipitation heat treatment or artificial aging curves for solution heat-treated aluminum alloy 6061

The above description of the precipitation process and its effects on strength and metallurgical structures applies not only to heat treatable binary compositions, none of which is used commercially, but also to the commercial alloys, having generally much greater complexity of composition. As noted before, not only do the mechanical properties change with these heat treatments, and with natural aging, but also physical properties (density and electrical and thermal conductivities) and electrochemical properties (solution potential). On the microstructural and submicroscopic scales, the electrochemical properties develop point-to-point nonuniformities that account for changes in corrosion resistance.

Measurements of changes in physical and electrochemical properties have played an important role in completely describing precipitation reactions and are very useful in analyzing or diagnosing whether heat treatable products have been properly or improperly heat treated. Although they may indicate the strength levels of products, they cannot be relied on to determine whether or not the product meets specified mechanical-property limits. Because elements in solid solution are always more harmful to electrical conductivity than the same elements combined with others as intermetallic compounds, thermal treatments are applied to ingots used for fabrication of electrical conductor products. These thermal treatments are intended to precipitate as much as possible of the dissolved impurities. Iron is the principal element involved, and, although the amount precipitated is only a few hundredths of a percent, the effect on electrical conductivity of the wire, cable, or other product made from the ingot is of considerable practical importance. These alloys may or may not be heat treatable with respect to mechanical properties. Electrical conductor alloys 6101 and 6201 are heat treatable.

These alloys are used in tempers in which their strengthening precipitate, the transition form of Mg_2Si, is largely out of solid solution to optimize both strength and conductivity.

The commercial heat treatable alloys are, with few exceptions, based on ternary or quaternary systems with respect to the solutes involved in developing strength by precipitation. The most prominent systems are: Al-Cu-Mg, Al-Cu-Si, and Al-Cu-Mg-Si, which are in the 2*xxx* and 2*xx.x* groups (wrought and casting alloys, respectively); Al-Mg-Si (6*xxx* wrought alloys); Al-Si-Mg, Al-Si-Cu, and Al-Si-Mg-Cu (3*xx.x* casting alloys); Al-Zn-Mg and Al-Zn-Mg-Cu (7*xxx* wrought and 7*xx.x* casting alloys); and Al-Li-Cu-Mg (8*xxx* wrought alloys). In each case, the solubility of the multiple solute elements decreases with decreasing temperatures, as shown in the solvus diagrams in *Alloy Phase Diagrams,* Volume 3, *ASM Handbook.* These diagrams show the equilibrium phase (or phases) that precipitates in a particular system. They do not show whether a transition phase occurs, nor do they provide its composition.

These multiple alloying additions of both major solute elements and supplementary elements employed in commercial alloys are strictly functional and serve with different heat treatments to provide the many different combinations of properties--physical, mechanical, and electrochemical--that are required for different applications. Some alloys, particularly those for foundry production of castings, contain amounts of silicon far in excess of the amount that is soluble or needed for strengthening alone. The function here is chiefly to improve casting soundness and freedom from cracking, but the excess silicon also serves to increase wear resistance, as do other microstructural constituents formed by manganese, nickel, and iron. Parts made of such alloys are commonly used in gasoline and diesel engines (pistons, cylinder blocks, etc.).

Alloys containing the elements silver and lithium are also capable of providing high strength with heat treatment and, in the case of lithium, both increased elastic modulus and lower density, which are highly advantageous--particularly for aerospace applications. Commercial use of alloys containing these elements has been restricted either by cost or by difficulties encountered in producing them.

In the case of alloys having copper as the principal alloying ingredient and no magnesium, strengthening by precipitation can be greatly increased by adding small fractional percentages of tin, cadmium, or indium, or combinations of these elements. Alloys based on these effects have been produced commercially but not in large volumes because of costly special practices and limitations required in processing and, in the case of cadmium, the need for special facilities to avoid health hazards from formation and release of cadmium vapor during alloying.

Strength at elevated temperatures is improved mainly by solid-solution and second-phase hardening, because, at least for temperatures exceeding those of the precipitation-hardening range--$\geq$230 °C (450 °F)--the precipitation reactions continue into the softening regime. For supersonic aircraft and space vehicle applications subject to aerodynamic heating, the heat treatable alloys of the 2*xxx* group can be used for temperatures up to $\sim$150 °C (300 °F). Aged rapidly solidified powder metallurgy alloys (Al-Fe-V-Si alloys) maintain usable strengths at temperatures as high as 315 °C (600 °F).

Effects of Strengthening on Other Mechanical Properties. Resistance to fatigue (from application of dynamic stresses into the tensile range) increases generally with increasing strength whether from alloying effects alone, from strain hardening, or from heat treatment. This improvement, in terms of either time to initiate cracks or cycles to failure, is generally less than the improvement in static strength, and the highest resistance to fatigue for a given alloy is sometimes provided by a temper having static strength levels lower than the highest strength possible--e.g., 2024-T3*x* or 2024-T4*x* versus 2024-T6*x* or 2024-T8*x*. This occurs mainly because the resistance to fatigue-crack growth at high levels of stress-intensity factor requires good fracture toughness, and this property decreases generally with increasing strength at high levels.

As strength, defined as resistance to deformation, increases, the properties of ductility, malleability, ease of forming, and fracture toughness tend to decrease. This inverse relationship between these properties and strength, however, is not universal. As indicated previously, for the non-heat-treatable alloys, the H2*x* or H3*x* tempers have advantages over those of the H1*x* series in the ductility/strength relationship. It is also true that, in the relationship of fracture toughness to yield strength, alloys of the 7*xxx* group (Al-Zn-Mg-Cu types) are superior to those of the 2*xxx* and 6*xxx* groups.

All of these properties must be carefully considered in application of alloys to critical engineering structures such as aircraft as well as to products such as truck wheels and other automotive and truck components. Good design, avoiding stress-concentrating features and any features that promote localized corrosion, is in most cases at least as important as good alloy and temper selection.

Other Considerations Involved in Alloy Development. The engineering properties and characteristics that have immediate effects on the functional behavior of end products is only a partial list of the features that must be considered in alloy design. One of the foremost considerations is that, to be economically viable, an alloy must be capable of being cast and fabricated to the form desired with reasonable freedom from scrap losses resulting from cracking or other in-process damage. Many alloys and specialty products, including those for extremely large-tonnage items such as beverage cans as well as Alclad products and brazing composites, are tailored to very specific uses, and cost-effective principles apply to the commercial viability of these also. All of these products must compete for markets with other metallic materials as well as polymeric materials, glasses, and ceramics.

Use of Aluminum Alloy Phase Diagrams

Although few products are sold and used in their equilibrium condition, equilibrium phase diagrams are an essential tool in understanding effects of composition and both solidification and solid-state thermal processing on microstructure. For aluminum alloys, phase diagrams are used to determine solidification and melting temperatures, the solidification path, and the equilibrium phases that form and their dissolution temperatures. In addition to determining appropriate temperatures for casting and thermal treatments, phase diagrams are used to determine the maximum levels for ancillary element additions of certain elements to prevent the crystallization of coarse primary particles. The most important liquid-to-solid transformations for aluminum alloys are the eutectic and the peritectic. Examples of phase diagrams illustrating eutectic and peritectic reactions are discussed in the following paragraphs, and phase diagrams for aluminum alloys are included in the Section "Structure and Properties of Metals" in this Handbook and in Volume 3 of the *ASM Handbook.*

The eutectic reaction is illustrated by the aluminum-copper system (Fig. 10). When the liquidus temperature of aluminum-rich alloys is reached during solidification, the liquid begins to solidify into a solid solution of copper in aluminum (α-aluminum). As temperature approaches the solidus, the α-aluminum becomes more enriched with copper. When the temperature falls below the solidus temperature in alloys containing less than the maximum solubility, 5.7% Cu, solidification is complete. At temperatures below the solvus, Al_2Cu particles precipitate, depleting the α-aluminum of copper. When cooled to room temperature under near-equilibrium conditions, the α-aluminum contains little copper, so strength is low. To increase strength, the material must be solution heat treated, quenched, and aged to develop metastable precipitates as described earlier in this article. In alloys containing more than 5.7% Cu, some liquid remains when the eutectic temperature is reached. This liquid solidifies at this temperature by a eutectic reaction to α-aluminum and Al_2Cu intermetallic particles. On cooling below the eutectic temperature, the α-aluminum rejects copper as Al_2Cu precipitates. It is important to realize that the eutectic reaction can occur in alloys containing less than the maximum solid solubility under commercial casting conditions, even though the equilibrium phase diagram does not predict that. Consequently, Al_2Cu particles form during solidification of most aluminum alloy ingots and shaped castings. Therefore, they are "preheated" or homogenized to dissolve the intermetallic particles.

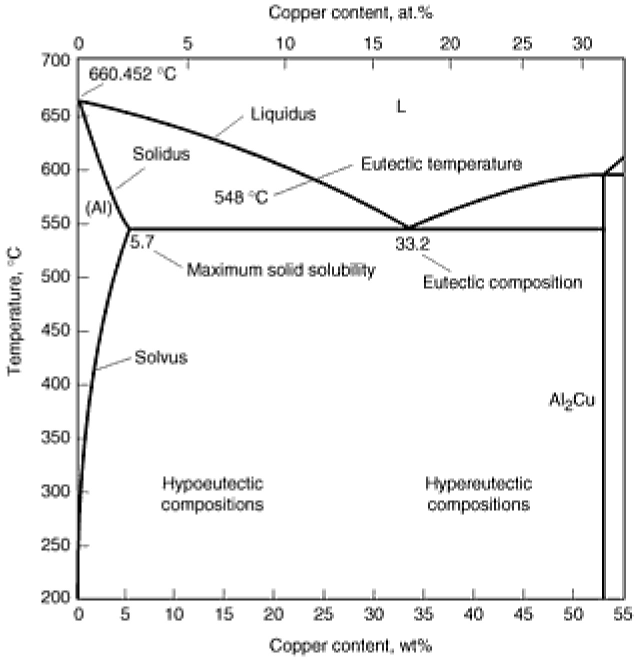


Fig. 10 Aluminum-copper phase diagram illustrating the eutectic reaction

The peritectic reaction in aluminum alloys is typified by the aluminum-chromium system (Fig. 11). During equilibrium solidification of alloys containing more than the peritectic composition, 0.41% Cr, but less than the maximum solid solubility of 0.77%, an intermetallic compound, Al_7Cr, forms when the liquidus temperature is reached. When the temperature falls to the peritectic temperature, 661 °C (1222 °F), the remaining liquid along with the Al_7Cr transforms to α-aluminum. Under commercial solidification conditions, however, the primary particles of Al_7Cr would not have the opportunity to transform to α-aluminum, so they would remain. Consequently, maximum chromium limits are established so that all of the chromium remains in supersaturated solid solution in the ingot. It precipitates as chromium-bearing dispersoids during ingot preheat.

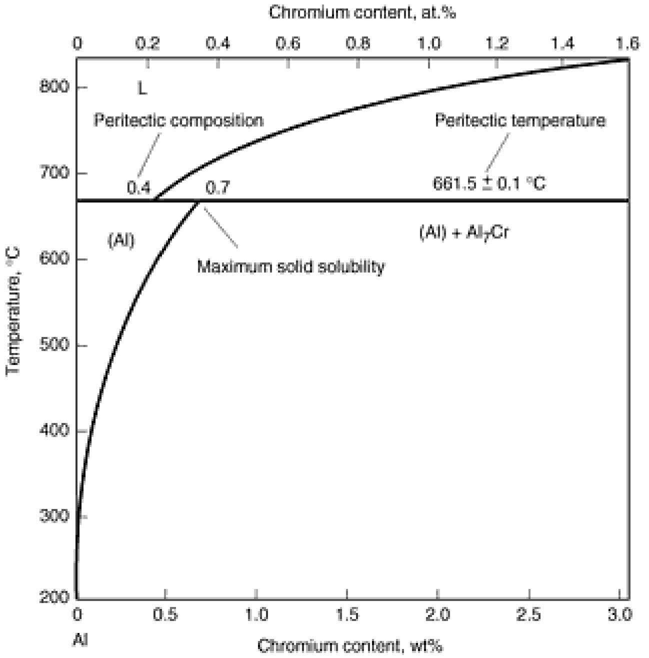


Fig. 11 Aluminum-chromium phase diagram illustrating the peritectic reaction

Alloying Effects on Phase Formation

All commercial aluminum alloys contain iron and silicon as well as two or more elements intentionally added to enhance properties. The phases formed and the function of the alloying elements are described below. Figure 1 summarizes the most common alloying additions in aluminum alloys.

Iron. Virtually all aluminum alloys contain some iron that is an impurity remaining after refining bauxite and smelting. The phase diagram predicts that during solidification of an aluminum-iron alloy containing a few tenths of a percent of iron, most of the iron remains in the liquid phase until a eutectic of solid solution plus Al_3Fe intermetallic constituent particles having a monoclinic crystal structure freezes. Depending on solidification rate and on the presence of other elements such as manganese, constituent particles of the metastable orthorhombic Al_6Fe phase can form instead of the equilibrium Al_3Fe. The maximum solid solubility of iron in aluminum is 0.05%, but the solubility is much lower in most structural alloys.

Silicon. This element is also a ubiquitous impurity in commercial aluminum alloys. Two ternary phases, cubic α $Al_{12}Fe_3Si$ and monoclinic β-$Al_9Fe_2Si_2$, form by a eutectic reaction. At low silicon contents, almost all of the iron is present as Al_3Fe. With increasing silicon contents, first the α- then the β-Al-Fe-Si phases appear. Phases in commercial products may not be those predicted by the equilibrium phase diagrams because of the long times at high temperatures required to approach equilibrium. In large amounts, silicon improves castability and fluidity. Consequently, it is used in 4*xxx* brazing sheet and in 3*xx.x* and 4*xx.x* casting alloys. Silicon ranges from about 5 to 20% in casting alloys.

Hypereutectic alloys (those containing >12.6% Si, the eutectic composition) are used for engine blocks because the primary silicon particles are wear resistant. Some 3*xx.x* casting alloys contain small additions of magnesium to render them capable of being age hardened.

Silicon is deliberately added to some alloys containing magnesium to provide precipitation hardening. The Al-Mg-Si system is the basis for the 6*xxx* alloys. At low magnesium contents, elemental silicon may be present as second-phase particles. As magnesium increases, both silicon particles and equilibrium hexagonal Mg_2Si constituents may be present. At higher magnesium contents, only Mg_2Si is present. Ternary alloys are strengthened by precipitation of metastable precursors to Mg_2Si. With the addition of copper, a complex quaternary $Al_4CuMg_5Si_4$ phase can form. A precursor to this quaternary phase strengthens Al-Cu-Mg-Si alloys.

Manganese. The aluminum-manganese system is the basis for the oldest aluminum alloys. Such alloys, known as 3*xxx*, are the most widely used wrought alloys because of their excellent formability and resistance to corrosion. Commercial aluminum-manganese alloys contain both iron and silicon. During solidification of commercial size ingots, some of the manganese forms Al_6(Mn,Fe) and cubic Al_{12}(Fe,Mn)Si by eutectic reactions. The remaining manganese remains in solution and is precipitated during the ingot preheat as Al_{12}(Mn,Fe)Si and Al_6(Mn,Fe) dispersoids. These dispersoids strengthen the material and control recrystallized grain size. In alloys containing copper, manganese precipitates as $Al_{20}Cu_2Mn_3$ dispersoid particles. Effects on strength are minor, but the dispersoids aid in grain size control after solution heat treatment.

Magnesium. The aluminum-magnesium system is the basis for the wrought 5*xxx* and cast 5*xx.x* non-heat-treatable aluminum alloys, which provide excellent combinations of strength and corrosion resistance by solid-solution strengthening and work hardening. Although in principle this phase diagram exhibits a positively sloping solvus, a necessary condition for a precipitation-hardening system, difficulty in nucleating the face-centered cubic (fcc) Al_3Mg_2 precipitates has precluded commercialization of heat-treatable aluminum-magnesium alloys, unless they contain enough silicon, copper, or zinc to form Mg_2Si, Al-Cu-Mg, or Al-Zn-Mg precipitates.

Copper. The aluminum-copper system is the basis for the wrought 2*xxx* and cast 2*xx.x* alloys, and many other heat-treatable alloys contain copper. In commercial aluminum-copper alloys, some of the copper chemically combines with aluminum and iron to form either tetragonal Al_7Cu_2Fe or orthorhombic α(Al,Cu,Fe) constituent particles during solidification. These constituents cannot be dissolved during subsequent thermal treatments, but one can transform to the other during thermal treatments of ingots or castings. During heat treatment of aluminum-copper alloys containing little magnesium, Al_2Cu precipitates as the strengthening phase.

Adding magnesium to aluminum-rich aluminum-copper alloys results in the formation of the Al_2CuMg phase by eutectic decomposition. Metastable precursors to face-centered orthorhombic Al_2CuMg precipitates are used to strengthen several structural alloys used in the aerospace industry because they confer a desirable combination of strength, fracture toughness, and resistance to the growth of fatigue cracks.

Zinc. This element confers little solid-solution strengthening or work hardening to aluminum, but Al-Zn-Mg precipitates provide the basis for the 7*xxx* wrought alloys and the 7*xx.x* cast alloys. Two phases can form by eutectic decomposition in commercial Al-Zn-Mg alloys: hexagonal $MgZn_2$ and body-centered cubic (bcc) $Al_2Mg_3Zn_3$. Depending on the zinc/magnesium ratio, copper-free alloys are strengthened by metastable precursors to either $MgZn_2$ or $Al_2Mg_3Zn_3$. In Al-Zn-Mg-Cu alloys, copper and aluminum substitute for zinc in $MgZn_2$ to form $Mg(Zn,Cu,Al)_2$. Al_2CuMg particles can also form in these alloys by eutectic decomposition and solid-state precipitation.

Chromium. In commercial alloys, the solubility can be reduced to such an extent that Al_7Cr primary particles can form by a peritectic reaction at chromium contents lower than that indicated by the binary aluminum-chromium phase diagram. Because coarse primary particles are harmful to ductility, fatigue, and fracture toughness, the upper limits of chromium depend on the amount and nature of the other alloying and impurity elements. In 5*xxx* alloys, fcc cubic $Al_{18}Mg_3Cr_2$ dispersoids precipitate during ingot preheating. In 7*xxx* alloys, the composition of the dispersoids is closer to $Al_{12}Mg_2Cr$. Chromium dispersoids contribute to strength in non-heat-treatable alloys and control grain size and degree of recrystallization in heat-treatable alloy products.

Zirconium. This element also forms a peritectic with aluminum. The phase diagram predicts that the equilibrium Al_3Zr phase is tetragonal, but fine dispersoids of metastable cubic Al_3Zr form during ingot preheating treatments. Most 7*xxx* and some 6*xxx* and 5*xxx* alloys developed since the 1960s contain small amounts of zirconium, usually less than 0.15%, to form Al_3Zr dispersoids for recrystallization control.

Lithium. This element reduces the density and increases the modulus of aluminum alloys. In binary alloys it forms metastable Al_3Li precipitates and combines with aluminum and copper in Al-Cu-Li alloys to form a large number of Al-Cu-Li phases. Because of its high cost relative to other alloying elements, lithium alloys have been found to be cost effective thus far only in space and military applications.

Aluminum Wrought Products

Introduction

COMMERCIAL WROUGHT ALUMINUM PRODUCTS can be divided into two groups. *Standardized* wrought products include sheet, plate, foil, rod, bar, wire, tube, pipe, and structural forms. *Engineered* wrought products are those designed for specific applications and include extruded shapes, forgings, and impacts. Typical examples of wrought products include plate or sheet, which is subsequently formed or machined into products such as aircraft or building components, household foil, and extruded shapes such as storm window frames.

Alloys Used for Wrought Products

Aluminum alloys are commonly grouped into an alloy designation series, as described in the article "Alloy and Temper Designations for Aluminum" in this Section. The general characteristics of the alloy groups are described below.

1*xxx* Series. Aluminum of 99.00% or higher purity has many applications, especially in the electrical and chemical fields. These grades of aluminum are characterized by excellent corrosion resistance, high thermal and electrical conductivities, low mechanical properties, and excellent workability. Moderate increases in strength may be obtained by strain hardening. Iron and silicon are the major impurities.

2*xxx* Series. Copper is the principal alloying element in 2*xxx* series alloys, often with magnesium as a secondary addition. These alloys require solution heat treatment to obtain optimum properties; in the solution heat-treated condition, mechanical properties are similar to, and sometimes exceed, those of low-carbon steel. In some instances, precipitation heat treatment (aging) is employed to further increase mechanical properties. This treatment increases yield strength, with attendant loss in elongation; its effect on tensile strength is not as great.

The alloys in the 2*xxx* series do not have as good corrosion resistance as most other aluminum alloys, and under certain conditions they may be subject to intergranular corrosion. Therefore, these alloys in the form of sheet usually are clad with a high-purity aluminum, a magnesium-silicon alloy of the 6*xxx* series, or an alloy containing 1% Zn. The coating, usually from $2\frac{1}{2}$ to 5% of the total thickness on each side, provides galvanic protection of the core material and thus greatly increases resistance to corrosion.

Alloys in the 2*xxx* series are particularly well suited for parts and structures requiring high strength-to-weight ratios and are commonly used to make truck and aircraft wheels, truck suspension parts, aircraft fuselage and wing skins, structural parts, and those parts requiring good strength at temperatures up to 150 °C (300 °F).

3*xxx* Series. Manganese is the major alloying element of 3*xxx* series alloys. These alloys generally are non-heat-treatable but have about 20% more strength than 1*xxx* series alloys. Because only a limited percentage of manganese (up to about 1.5%) can be effectively added to aluminum, manganese is used as a major element in only a few alloys. However, one of these, the popular 3003 alloy, is widely used as a general-purpose alloy for moderate-strength applications requiring good workability.

4*xxx* Series. The major alloying element in 4*xxx* series alloys is silicon, which can be added in sufficient quantities (up to 12%) to cause substantial lowering of the melting range without producing brittleness. For this reason, aluminum-silicon alloys are used in welding wire and as brazing alloys for joining aluminum, where a lower melting range than that of the base metal is required. Most alloys in this series are non-heat treatable, but when used in welding heat-treatable alloys, they pick up some of the alloying constituents of the latter and so respond to heat treatment to a limited extent. The alloys containing appreciable amounts of silicon become dark gray to charcoal when anodic oxide finishes are applied and hence are in demand for architectural applications. Alloy 4032 has a low coefficient of thermal expansion and high wear resistance; thus it is well suited to production of forged engine pistons.

5*xxx* Series. The major alloying element in 5*xxx* series alloys is magnesium. When it is used as a major alloying element or with manganese, the result is a moderate-to-high-strength work-hardenable alloy. Magnesium is considerably more effective than manganese as a hardener, about 0.8% Mg being equal to 1.25% Mn, and it can be added in considerably higher quantities. Alloys in this series possess good welding characteristics and good resistance to corrosion in marine atmospheres. However, certain limitations should be placed on the amount of cold work and the safe operating temperatures permissible for the higher-magnesium alloys (over ~3.5% for operating temperatures above ~65 °C, or 150 °F) to avoid susceptibility to stress-corrosion cracking.

6*xxx* Series. Alloys in the 6*xxx* series contain silicon and magnesium approximately in the proportions required for formation of magnesium silicide (Mg_2Si), thus making them heat treatable. Although not as strong as most 2*xxx* and 7*xxx* alloys, 6*xxx* series alloys have good formability, weldability, machinability, and corrosion resistance, with medium strength. Alloys in this heat-treatable group may be formed in the T4 temper (solution heat treated but not precipitation heat treated) and strengthened after forming to full T6 properties by precipitation heat treatment.

7*xxx* Series. Zinc, in amounts of 1 to 8%, is the major alloying element in 7*xxx* series alloys, and when coupled with a smaller percentage of magnesium results in heat-treatable alloys of moderate to very high strength. Usually other elements, such as copper and chromium, are added in small quantities. Dilute additions of scandium also improve properties. 7*xxx* series alloys are used in airframe structures, mobile equipment, and other highly stressed parts.

Higher strength 7*xxx* alloys exhibit reduced resistance to stress corrosion cracking and are often utilized in a slightly overaged temper to provide better combinations of strength, corrosion resistance, and fracture toughness.

8*xxx* series alloys constitute a wide range of chemical compositions. For example, improved elevated-temperature performance is achieved through the use of dispersion-strengthened Al-Fe-Ce alloys (e.g., 8019) or Al-Fe-V-Si alloys (e.g., 8009) made by powder metallurgy processing. Lower density and higher stiffness can be achieved in lithium-containing alloys (e.g., 8090). The latter alloy, which is precipitation hardenable, has replaced medium-to-high strength 2*xxx* and 7*xxx* alloys in some aircraft/aerospace applications (e.g., helicopter components).

General Characteristics of Wrought Products

Wrought products are those that have been shaped by plastic deformation. This deformation, which is done by hot and cold working processes such as rolling, extruding, forging, and drawing, either singly or in combination, transforms the cast ingot into the desired product form. As the deformation proceeds, the metallurgical structure also changes from a cast structure to a fully wrought structure. In this process, grain size and shape may be radically changed, the final configuration depending on the entire thermomechanical history (including any final annealing stages or heat treatments). During deformation, the second-phase microconstituents present in irregular forms in the ingot are fragmented into more equiaxed particles, which tend to align in the direction of greatest extension. The grains are usually also elongated in this direction and thinned or flattened in flat rolled products, in thin extruded products, and in the flash-plane areas of die forgings. Thus, the wrought metallurgical structure has directionality, the degree of which depends on the directionality of the deformation imposed during shaping of the product.

These changes in metallurgical structure are accompanied by changes in properties, particularly mechanical properties, which are generally higher in the wrought products than in the cast ingot from which they originate. The wrought products generally exhibit some pronounced directionality of mechanical properties (i.e., anisotropy), which is negligible in the ingot from which they are produced. The directionality in sheet is not pronounced with respect to tensile properties but can be quite significant with respect to performance in deep drawing or cupping operations. Nonuniformity in different directions in the plane of the sheet causes formation of protuberances called "ears" in circular cups. These are primarily the result of crystallographic texture in the sheet, a nonrandom or preferred orientation of the grains (see the following discussion on "Crystallographic Texture"). For deep drawing and cupping operations such as those employed in making beverage and food cans, special "non-earing quality" sheet is supplied.

Thicker products that can be stressed or tested in three orthogonal directions generally exhibit differences in tensile and compressive properties as well as in resistance to fatigue stresses and stress-corrosion cracking in the three directions. With respect to these characteristics, the longitudinal direction (that in which the product was lengthened or extended most in working, as shown in Fig. 1) generally is superior. In the long-transverse direction (which may be either an extension or compression direction, as shown in Fig. 1, but with less extension or less compression than either of the other two directions), the properties and resistance are intermediate to those of the other directions. In the short transverse direction (direction of greatest compression in working, as shown in Fig. 1), the properties and resistance are generally lower than in the other directions. In most cases the longitudinal, long-transverse, and short-transverse directions correspond to the greatest, intermediate, and smallest dimensions of product having a rectangular cross section. For products of axisymmetric cross section (round, square, hexagonal, etc.), there is no long- and short-transverse distinction; any direction in the cross-sectional plane is regarded as transverse (Fig. 2).

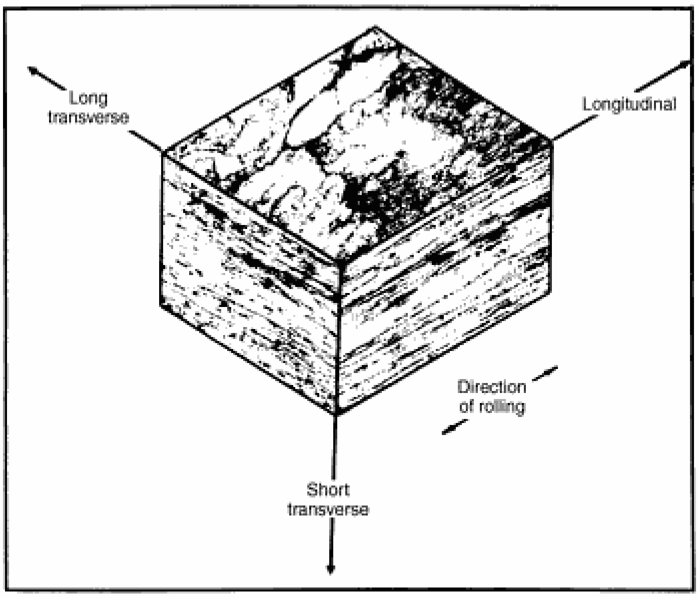


Fig. 1 Composite of micrographs of flat-rolled 7075-T6 illustrating metallurgical structure directionality. 40×

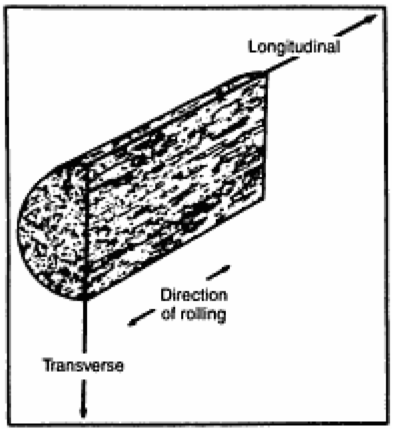


Fig. 2 Composite of micrographs of 7075-T6 rod illustrating metallurgical structure directionality. 40×

The influence of directionality on mechanical properties is shown in Fig. 3 for two closed-die forgings. Variation in properties is obtained because of the variations in thickness, variations in reduction during forging, and variation in angle between the axis of the test specimen and the direction of grain flow. Both die forgings show markedly lower properties in the short transverse direction than in the longitudinal direction.

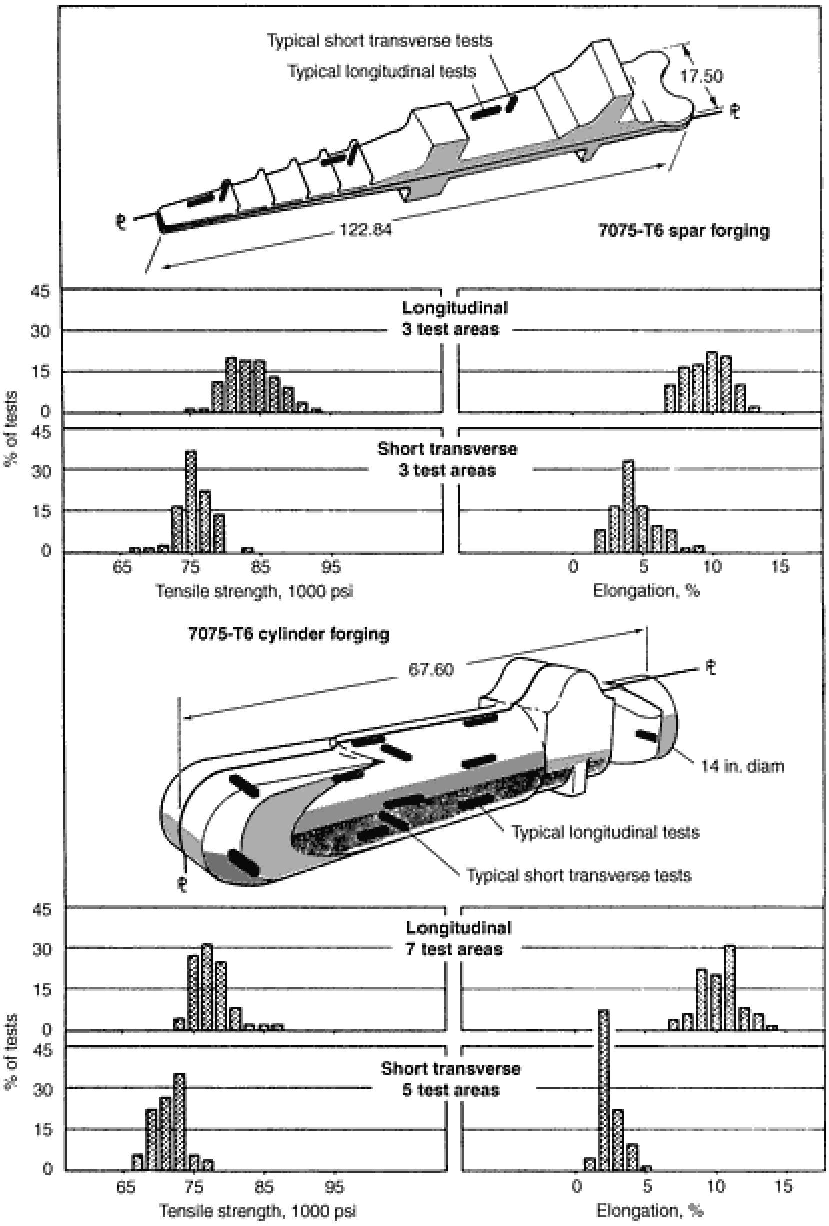


Fig. 3 Variation in mechanical properties for two different 7075-T6 aluminum alloy forgings. Both were forged on a 35,000 ton press, solution treated at 470 °C (880 °F) for 3 h, quenched in water at 60 °C (140 °F), and aged at 120 °C (250 °F) for 24 h. Spar forging (shown at top): Cast ingots were received in 17 lots from three sources. Two lots were in 480 mm (19 in.) rounds, and 15 lots were in 250 to 300 mm (10 to 20 in.) squares. Twenty-eight forgings were tested at the locations indicated. Cylinder forging (shown at bottom): All cylinders were forged from 480 mm (19 in.) rounds. Six of the forgings were tested at locations shown.

Fatigue strength of bars cut from forgings is affected in the same manner as tensile strength, yield strength, and elongation. Figure 4 shows the results of fatigue tests of specimens cut from two sample forgings in directions both parallel and transverse to the forging flow lines. Once again, properties are superior in the longitudinal direction.

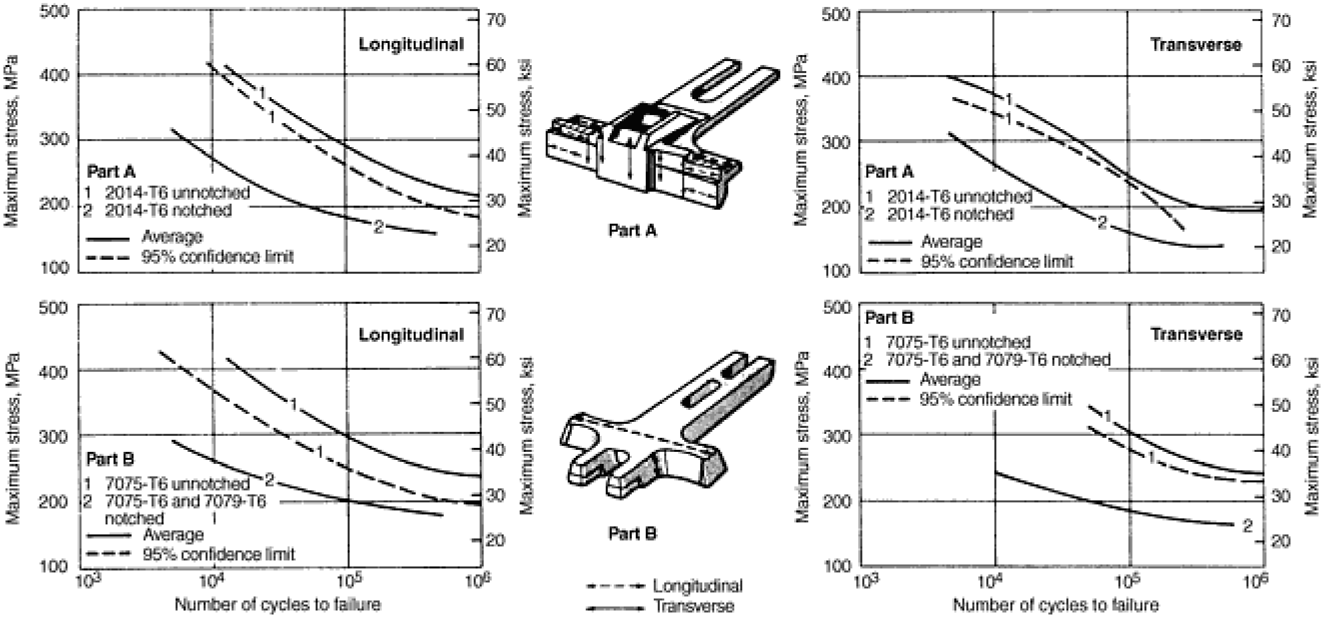


Fig. 4 Effect of alloy, design, and directionality on the axial fatigue strength of aluminum alloy forgings. Data apply to parts A and B, as shown. Sheet-type fatigue specimens, 3.2 mm (0.125 in.) thick and 6.4 mm (0.250 in.) wide, were cut both parallel and transverse to the forging flow lines. Locations from which specimens were taken are shown on the drawings. Mean stress was 91.7 MPa (13.3 ksi); notch was 1.2 mm (0.047 in.) in diameter hole in center of specimen. K_t = 2.5.

Directionality is considerably affected by whether the grain structure is recrystallized or unrecrystallized, the latter condition generally being more highly directional (see the following discussion on "Grain Structure"). In the case of heat treated extruded shapes, there is usually a very thin surface or peripheral layer of recrystallized grain structure surrounding an unrecrystallized core. Since the recrystallized grain material is somewhat less resistant to fatigue than the unrecrystallized structure, its thickness should be minimized. For critical applications, a considerable percentage of the length from the rear of the extrusion is discarded to accomplish this, because the recrystallized layer thickness increases from front to rear of the extrusion. In the most critical applications, complete removal of the recrystallized materials by machining or chemical milling may be required.

Extrusions, which generally have unrecrystallized structures, exhibit somewhat higher directionality of tensile properties than rolled products of equivalent cross section that also are unrecrystallized. This difference, primarily evidenced by higher longitudinal strength values in the extruded product, which may be as much as 10% higher, is attributed to more pronounced preferred grain orientation generated by the deformation of extrusion.

Grain Structure. The grain size of aluminum alloy ingots and castings is typically controlled by the introduction of inoculants that form intermetallic compounds containing titanium and/or boron. During deformation processing, the grain structure becomes modified. Most aluminum alloy products undergo dynamic recovery during hot working as the dislocations form networks of subgrains. New dislocation-free grains may form between and following rolling passes (static recrystallization) or during deformation processing (dynamic recrystallization). During deformation, the crystal lattice of the aluminum matrix rotates at its interfaces between constituent and coarse precipitate particles. These high-energy sites serve to nucleate recrystallization. This process is termed particle-stimulated nucleation and is an important mechanism in the recrystallization process of aluminum. The particle size that will serve as a nucleus decreases as deformation temperature decreases and strain and strain rate increase. Dispersoid particles retard the movement of high-angle grain boundaries. Consequently, hot-worked structures are resistant to recrystallization and often retain the dynamically recovered subgrain structure in the interiors of elongated cast grain boundaries. In heat-treated products containing a sufficient quantity of dispersoids, the unrecrystallized structure of hot-worked plate, forgings, and extrusions can be retained after solution heat treatment.

Degree of recrystallization of hot-worked products has an effect on fracture toughness. Unrecrystallized products develop higher toughness than do products that are either partially or completely recrystallized. This behavior is attributed to precipitation on the recrystallized high-angle grain boundaries during the quench. These particles increase the tendency for low-energy intergranular fracture. Products such as sheet, rods, and tubing that are cold rolled invariably recrystallize during solution heat treatment or annealing to O temper.

Decreasing the grain size can increase strength of 5*xxx* alloy products in the O temper by 7 to 28 MPa (1 to 4 ksi), but grain size is not a major factor in increasing strength of other aluminum alloy products. Several measures of formability are influenced by grain size, however, so grain size is controlled for this reason. One particular use of grain size control is to produce stable, fine grains, which are essential in developing super-plastic behavior in aluminum alloy sheet.

Crystallographic Texture. Cast aluminum ingots and shapes generally have a random crystallographic texture; the orientation of the unit cells comprising each grain are not aligned. With deformation, however, certain preferred crystallographic orientations develop. Many of the grains rotate and assume certain orientations with respect to the direction of deformation. For flat-rolled products and extrusions having a high aspect ratio of width to thickness, the deformation texture is similar to that in pure fcc metals. These orientations are described by using the Miller indices of the planes {nnn} in the grains parallel to the plane of the worked product and directions {nnn} parallel to the working direction. The predominant textures are {110}[112], {123}[634], and {112}[111]. During recrystallization, a high concentration of grains in the {001}[100] or {011}[100] orientations may develop. Alternatively, if particle-stimulated nucleation is present to a large extent, the recrystallized texture will be random. Control of crystallographic texture is particularly important for non-heat-treatable sheet that will be drawn. If texture is not random, ears form during the drawing process. In extruded or drawn rod or bar, the texture is a dual-fiber texture in which almost all grains are aligned so that the grain directions are either [001] or [111]. In heat-treatable alloys, texture has the most potent effect on the properties of extrusions that have the dual-fiber texture. Strengthening by this process is so potent that the longitudinal yield strengths of extruded products exhibiting this texture are about 70 MPa (10 ksi) higher than strength in the transverse direction. If this dual-fiber texture is lost by recrystallization, strength in the longitudinal direction decreases to that in the transverse directions.

Product Forms

Table 1 summarizes the various product forms in which commonly used wrought aluminum alloys are available. Recommended tempers are also listed. Temper designations are described in the article "Alloy and Temper Designation Systems for Aluminum" in this Section.

Table 1 Wrought alloy products and tempers

Alloy	Sheet	Plate	Tube		Pipe	Structural profiles (shapes)(a)	Extruded wire, rod, bar, and profiles (shapes)	Rolled or cold-finished			Rivets	Forgings and forging stock	Foil	Fin stock
			Drawn	**Extruded**				**Rod**	**Bar**	**Wire**				
1050	. . .	. . .	. . .	H112	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1060	O, H12, H14, H16, H18	O, H12, H14, H112	O, H12, H14, H18, H113	O, H112	. . .	. . .	. . .	H14	. . .	. . .	. . .	. . .	. . .	. . .
1100	O, H12, H14, H16, H18	O, H12, H14, H112	O, H12, H14, H16, H18, H113	O, H112	. . .	. . .	O, H112	O, H112, H14, F	O, H112, F	O, H112, H12, H14, H16, H18	O, H14	H112, F	O, H19	O, H14, H18, H19, H25, H111, H113, H211
1145	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	O, H19	O, H14, H19, H25, H111, H113, H211
1200	. . .	. . .	. . .	H112	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1235	. . .	. . .	. . .	H112	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	O, H19	. . .
1345	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	O, H12, H14, H16, H18, H19	. . .	. . .	. . .	. . .
1350(b)	O, H12, H14,	O, H12,	. . .	H111	H111	H111	H111	O, H12, H14,	H12,	O, H12, H14, H16,	. . .	. . .	. . .	. . .

	H16, H18	H14, H112						H16, H22, H24, H26	H111	H19, H22, H24, H26				
2011	. . .	. . .	T3, T4511, T8	. . .	. . .	. . .	. . .	T3, T4, T451, T8	T3, T4, T451, T8	T3, T8	. . .	. . .	. . .	. . .
2014	O, T3, T4, T6	O, T451, T651	O, T4, T6	O, T4, T4510, T4511, T6, T6510, T6511	. . .	. . .	O, T4, T4510, T4511, T6, T6510, T6511	O, T4, T451, T6, T651	O, T4, T451, T6, T651	O, T4, T6	. . .	F, T4, T6, T652	. . .	. . .
Alclad 2014	O, T3, T4, T6	O, T451, T651	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
2017	. . .	. . .	. . .	. . .	. . .	. . .	. . .	O, H13, T4, T451	O, T4, T451	O, H13, T4	T4	. . .	. . .	. . .
2018	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	F, T61	. . .	. . .
2024	O, T3, T361, T4, T72, T81, T861	O, T351, T361, T851, T861	O, T3	O, T3, T3510, T3511, T81, T8510, T8511	. . .	. . .	O, T3, T3510, T3511, T81, T8510, T8511	O, H13, T351, T4, T6, T851	O, T351, T4, T6, T851	O, H13, T36, T4, T6	T4	. . .	. . .	. . .
Alclad 2024	O, T3, T361, T4, T81, T861	O, T351, T361, T851, T861	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Alclad one side 2024	O, T3, T361, T81, T861	O, T351, T361, T851, T861	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

$1\frac{1}{2}$ % Alclad 2024	O, T3, T361, T81, T861	O, T351, T361, T851, T761	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
$1\frac{1}{2}$ % Alclad one side 2024	O, T3, T361, T81, T861	O, T351, T361, T851, T861	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
2025	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	F, T6	. . .	. . .
2036	T4	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
2117	. . .	. . .	. . .	. . .	. . .	. . .	. . .	O, H13, H15	. . .	O, H13, H15	T4	. . .	. . .	. . .
2124	. . .	T851	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
2218	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	F, T61, T72	. . .	. . .
2219	O, T31, T37, T81, T87	O, T351, T37, T851, T87	. . .	O, T31, T3510, T3511, T81, T8510, T8511	. . .	. . .	O, T31, T3510, T3511, T81, T8510, T8511	T851	T851	. . .	. . .	F, T6, T852	. . .	. . .
Alclad 2219	O, T31, T37, T81, T87	O, T351, T37, T851, T87	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
2618	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	F, T61	. . .	. . .

3003	O, H12, H14, H16, H18	O, H12, H14, H112	O, H12, H14, H16, H18, H25, H113	O, H112	H18, H112	. . .	O, H112	O, H112, F, H14	O, H112, F	O, H112, H12, H14, H16, H18	O, H14	H112, F	O, H19	O, H14, H18, H19, H25, H111, H113, H211
Alclad 3003	O, H12, H14, H16, H18	O, H12, H14, H112	O, H14, H18, H25, H113	O, H112	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
3004	O, H32, H34, H36, H38	O, H32, H34, H112	O, H34, H36, H38	O	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Alclad 3004	O, H32, H34, H36, H38	O, H32, H34, H112	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
3005	O, H12, H14, H16, H18, H19, H26, H28	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
3105	O, H12, H14, H16, H18, H25	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
4032	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	F, T6	. . .	. . .
5005	O, H12, H14, H16, H18,	O, H12, H14, H32, H34, H112	. . .	. . .	. . .	. . .	. . .	O, H12, H14, H16, H22,	. . .	O, H19, H32	O, H32	. . .	. . .	. . .

	H32, H34, H36, H38							H24, H26, H32						
5050	O, H32, H34, H36, H38	O, H112	O, H32, H34, H36, H38	. . .	. . .	. . .	. . .	O, F	O, F	O, H32, H34, H36, H38	. . .	. . .	. . .	. . .
5052	O, H32, H34, H36, H38	O, H32, H34, H112	O, H32, H34, H36, H38	. . .	. . .	. . .	. . .	O, F, H32	O, F	O, H32, H34, H36, H38	O, H32	. . .	O, H19	. . .
5056	. . .	. . .	. . .	. . .	. . .	. . .	. . .	O, F, H32	O, F	O, H111, H12, H14, H18, H32, H34, H38, H192, H392	O, H32	. . .	H19	. . .
Alclad 5056	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	H192, H392, H393	. . .	. . .	. . .	. . .
5083	O, H116, H321	O, H112, H116, H321	. . .	O, H111, H112	. . .	. . .	O, H111, H112	. . .	. . .	. . .	. . .	H111, H112, F	. . .	. . .
5086	O, H112, H116, H32, H34, H36, H38	O, H112, H116, H32, H34	O, H32, H34, H36	O, H111, H112	. . .	. . .	O, H111, H112	. . .	. . .	. . .	. . .	. . .	. . .	. . .
5154	O, H32, H34, H36, H38	O, H32, H34, H112	O, H34, H38	O, H112	. . .	. . .	O, H112	O, H112, F	O, H112, F	O, H112, H32, H34, H36, H38	. . .	. . .	. . .	. . .

5252	H24, H25, H28	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
5254	O, H32, H34, H36, H38	O, H32, H34, H112	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
5454	O, H32, H34	O, H32, H34, H112	H32, H34	O, H111, H112	. . .	. . .	O, H111, H112	. . .	. . .	. . .	. . .	. . .	. . .	. . .
5456	O, H116, H321	O, H112, H116, H321	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	H112, F	. . .	. . .
5457	O	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
5652	O, H32, H34, H36, H38	O, H32, H34, H112	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
5657	H241, H25, H26, H28	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6005	. . .	. . .	. . .	T1, T5	. . .	. . .	T1, T5	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6053	. . .	. . .	. . .	. . .	. . .	. . .	. . .	O, H13	. . .	O, H13	T61	F, T6	. . .	. . .
6061	O, T4, T6	O, T451, T651	O, T4, T6	O, T1, T4, T4510, T4511, T51, T6, T6510, T6511	T6	T6	O, T1, T4, T4510, T4511, T51, T6, T6510, T6511	O, H13, T4, T451, T6, T651	O, T4, T451, T6, T651	O, H13, T4, T6, T89, T913, T94	T6	F, T6, T652	. . .	. . .

Alclad 6061	O, T4, T6	O, T451, T651	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6063	. . .	. . .	O, T4, T6, T83, T831, T832	O, T1, T4, T5, T52, T6	T6	. . .	O, T1, T4, T5, T52, T6	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6066	. . .	. . .	O, T4, T6	O, T4, T4510, T4511, T6, T6510, T6511	. . .	. . .	O, T4, T4510, T4511, T6, T6510, T6511	. . .	. . .	. . .	. . .	F, T6	. . .	. . .
6070	. . .	. . .	. . .	T6	. . .	. . .	T6	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6101(b)	. . .	. . .	. . .	T6, T61, T63, T64, T65, H111	T6, T61, T63, T64, T65, H111	T6, T61, T63, T64, T65, H111	T6, T61, T63, T64, T65, H111	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6105	. . .	. . .	. . .	T1, T5	. . .	. . .	T1, T5	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6151	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	F, T6, T652	. . .	. . .
6162	. . .	. . .	. . .	. . .	. . .	. . .	T5, T5510, T5511, T6, T6510, T6511	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6201(b)	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	T81	. . .	. . .	. . .	. . .
6262	. . .	. . .	T6, T9	T6, T6510, T6511	. . .	. . .	T6, T6510, T6511	T6, T651, T9	T6, T651, T9	T6, T9	. . .	. . .	. . .	. . .

6351	. . .	. . .	. . .	T4, T6	T4, T6	. . .	T1, T4, T5, T51, T54, T6	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6463	. . .	. . .	. . .	. . .	. . .	. . .	T1, T5, T6	. . .	. . .	. . .	. . .	. . .	. . .	. . .
7005	. . .	. . .	. . .	. . .	. . .	. . .	T53	. . .	. . .	. . .	. . .	. . .	. . .	. . .
7049	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	T73, T7352	. . .	. . .
7050	. . .	T7451(c), T7651	. . .	. . .	. . .	. . .	T73510, T73511, T74510(c), T74511(c), T76510, T76511	H13	. . .	H13	T7	T74(c), T7452(c), F	. . .	. . .
7072	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	O, H14, H18, H19, H23, H24, H241, H25, H111, H113, H211
7075	T6, T73, T76	O, T651, T7351, T7651	O, T6, T73	O, T6, T6510, T6511, T73, T73510, T73511	. . .	. . .	O, T6, T6510, T6511, T73, T73510, T73511, T76, T76510, T76511	O, H13, T6, T651, T73, T7351	O, T6, T651, T73, T735	O, H13, T6, T73	T6, T73	F, T6, T652, T73, T7352	. . .	. . .
Alclad 7075	O, T6, T73, T76	O, T651, T7351, T7651	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

Alclad one side 7075	O, T6	O, T651	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
7008 Alclad 7075	O, T6, T76	O, T651, T7651	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
7175	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	F, T74, T7452(c), T7454(c), T66	. . .	. . .
7178	O, T6, T76	O, T651, T7651	. . .	. . .	. . .	. . .	O, T6, T6510, T6511, T76, T76510, T76511	O, H13	. . .	O, H13	T6	. . .	. . .	. . .
Alclad 7178	O, T6, T76	O, T651, T7651	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
7475	T61, T761	T651, T7351, T7651	. . .	. . .	. . .	. . .	. . .	O	. . .	. . .	. . .	. . .	. . .	. . .
Alclad 7475	T61, T761	T651, T7651	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
8017	. . .	. . .	. . .	. . .	. . .	. . .	. . .	H12, H22	. . .	H212	. . .	. . .	. . .	. . .
8030	. . .	. . .	. . .	. . .	. . .	. . .	. . .	H12	. . .	H221	. . .	. . .	. . .	. . .
8176	. . .	. . .	. . .	. . .	. . .	. . .	. . .	H14	. . .	H24	. . .	. . .	. . .	. . .

8177	. . .	. . .	. . .	. . .	. . .	. . .	. . .	H13, H23	. . .	H221	. . .	. . .	. . .	. . .

Source: *Aluminum Standards and Data 1997,* The Aluminum Association Inc., March 1997

(a) Rolled or extruded.

(b) Products listed for these alloys are for electric conductors only.

(c) T74-type tempers, although not previously registered, have appeared in various literature and specifications as T736-type tempers.

Flat-Rolled Products

Flat-rolled products include plate, sheet, and foil. These products are semifabricated to rectangular cross section by sequential reductions in the thickness of cast ingot by hot and cold rolling. Properties in work-hardened tempers are controlled by degree of cold reduction, partial or full annealing, and the use of stabilizing treatments. Plate, sheet, and foil produced in heat-treatable compositions may be solution heat treated, quenched, precipitation hardened, and thermally or mechanically stress relieved.

Sheet and foil may be rolled with textured surfaces. Sheet and plate rolled with specially prepared work rolls may be embossed to produce products such as tread plate. By roll forming, sheet in corrugated or other contoured configurations can be produced for such applications as roofing, siding, ducts, and gutters.

Plate refers to a product having a thickness greater than 6.3 mm (0.250 in.). Plate up to 200 mm (8 in.) thick is available in some alloys. Extra-large plates--e.g., 22 mm ($\frac{7}{8}$ in. thick) by 2.25 m (89 in.) wide by 32 m (105 ft) long--are supplied for construction of the wings of wide-body aircraft. Plate usually has either sheared or sawed edges and can be cut into circles, rectangles or odd-shape blanks. Plate of certain alloys--notably the high-strength 2*xxx* and 7*xxx* series alloys--also is available in clad form. The most commonly used plate alloys are 2024, 2124, 2219, 7050, 7178, and 7475 for aircraft structures; 5083, 5086, and 5456 for marine, cryogenic and pressure-vessel applications, and 1100, 3003, 5052, and 6061 for general applications. Table 1 lists the various alloys that are commonly forged.

Sheet. When a flat rolled product is over 0.15 through 6.3 mm (0.006 through 0.249 in.) in thickness, it is classified as "sheet". Sheet edges can be sheared, slit or sawed. Sheet is supplied in flat form, in coils, or in pieces cut to length from coils. Current facilities permit production of a limited amount of extra-large sheet, for example, up to 5 m (200 in.) wide by 25 m (1000 in.) long. Aluminum sheet is available in several surface finishes that range from "mill finishes," which have uncontrolled surface appearance that may vary from sheet to sheet, to bright finishes on one or two sides, to "aircraft skin quality." It may also be supplied embossed, patterned, painted, or otherwise surface treated, and with combinations of such treatments. Special products include corrugated, V-beam, and ribbed roofing and siding, duct sheet, fin stock, recording circles, and computer memory disks.

Among standard products are the alclad composites, which consists of heat treated 2*xxx* or 7*xxx* alloys clad on either or both sides with an appropriate anodic alloy or with aluminum. For sheet thicknesses, cladding thickness may range from $1\frac{1}{2}$ to as much as 10% of sheet thickness, the greater percentages applying to thinner products. A series of products termed "brazing sheet" is available. These products are also composites clad one or both sides with brazing alloy. For architectural uses, clad non-heat-treatable alloys may be supplied. These provide a variety of special finishing characteristics, integral color finishing capability, greater uniformity in appearance, and improved corrosion resistance.

With a few exceptions, most alloys in the 1*xxx*, 2*xxx*, 3*xxx*, 5*xxx*, and 7*xxx* series are available in sheet form (see Table 1). Along with alloy 6061, they cover a wide range of applications from builders' hardware to transportation equipment and from appliances to aircraft structures. Alloys 6009, 6111, and 6022 are widely used for automobile body panels and hood and deck stampings.

Foil is a product up through 0.15 mm (0.006 in.) thick. Most foil is supplied in coils, although it is also available in rectangular form (sheets). One of the largest end uses of foil is household wrap. There is a wider variety of surface finishes for foil than for sheet. Foil often is treated chemically or mechanically to meet the needs of specific applications. Common foil alloys are 1100, 1145, 1235, 3003, 5052, and 5056 (Table 1). Higher-strength foil of alloy 2024, 5052, or 5056 is used to produce the honeycomb cores used in bonded honeycomb sandwich panels.

Bar, Rod, and Wire

Bar, rod, and wire are defined as solid products that are extremely long in relation to their cross-section. They differ from each other only in cross-sectional shape and in thickness or diameter. When the cross section is round or nearly round and is over 10 mm ($\frac{3}{8}$ in.) in diameter, it is called *rod*. It is called *bar* when the cross section is square, rectangular, or in the shape of a regular polygon and when at least one perpendicular distance between parallel faces (thickness) is over 10 mm. *Wire* refers to a product, regardless of its cross-sectional shape, whose diameter or greatest perpendicular distance between parallel faces is 10 mm or less.

Rod and bar can be produced by either hot rolling or hot extruding and brought to final dimensions with or without additional cold working. Wire usually is produced and sized by drawing through one or more dies, although roll flattening also is used. Alclad rod or wire for additional corrosion resistance is available only in certain alloys. Many aluminum alloys are available as bar, rod, and wire; among these alloys, 2011 and 6262 are specially designed for screw-machine products, and 2117 and 6053 for rivets and fittings (Table 1). Alloy 2024-T4 is a standard material for bolts and screws. Alloys 1350, 6101, and 6201 are extensively used as electrical conductors. Alloy 5056 is used for zippers, and alclad 5056 for insect-screen wire.

Tubular Products

Tubular products include tube and pipe. They are hollow wrought products that are long in relation to their cross section and have uniform wall thickness except as affected by corner radii. Tube is round, elliptical, square, rectangular or regular polygonal in cross section. When round tubular products are in standardized combinations of outside diameter and wall thickness, commonly designated by "nominal pipe sizes" and "ANSI schedule numbers," they are classified as pipe.

Tube and pipe may be produced from a hollow extrusion ingot, by piercing a solid extrusion ingot, or by extruding through a porthole die or bridge die. They also may be made by forming and welding sheet. Tube may be brought to final dimensions by drawing through dies. Tube (both extruded and drawn) for general applications is available in such alloys as 1100, 2014, 2024, 3003, 5050, 5086, 6061, 6063, and 7075 (Table 1). For heat-exchanger tube, alloys 1060, 3003, alclad 3003, 5052, 5454, and 6061 are most widely used. Clad tube is available only in certain alloys and is clad only on one side (either inside or outside). Pipe is available in alloy 1350, 3003, 6061, 6063, 6101, and 6351 (Table 1).

Shapes

Shapes are products that are long in relation to their cross-sectional dimensions and that have cross-sectional shapes other than those of sheet, plate, rod, bar, wire, or tube. Most shapes are produced by extruding or by extruding plus cold finishing; shapes are now rarely produced by rolling because of economic advantages of the extrusion process. Shapes may be solid, hollow (with one or more voids), or semihollow. The 6*xxx* series (Al-Mg-Si) alloys, because of their easy extrudability, are the most popular alloys for producing shapes. Alloys of the 2*xxx* and 7*xxx* series are used in applications requiring higher strength.

Standard structural shapes such as I-beams, channels, and angles produced in alloy 6061 are made in different and fewer configurations than similar shapes made of steel; the patterns especially designed for aluminum offer better section properties and greater structural stability than those designed for steel, as a result of more efficient metal usage. The dimensions, weights, and properties of the alloy 6061 standard structural shapes, along with other information needed by structural engineers and designers, are contained in the *Aluminum Construction Manual*, published by the Aluminum Association, Inc.

Most aluminum alloys can be obtained as precision extrusions with good as-extruded surfaces; major dimensions usually do not need to be machined, because tolerances of the as-extruded product often permit manufacturers to complete the part by simple cutoff, drilling, or other minor operations.

In many instances, long aircraft structural elements incorporate large attachment fittings at one end. Such elements often are more economical to machine from stepped aluminum extrusions, with two or more cross sections in one piece, rather than from extrusions of uniform cross section that are large enough for the attachment fittings.

Aluminum shapes are produced in a great variety of cross-sectional designs that place the metal where it is needed to meet functional and appearance requirements. Full utilization of this capability of the extrusion process depends on the ingenuity of designers in creating new and useful configurations. However, the alloy extruded and the cross-sectional design greatly influence tooling cost, production rate, surface finish, and production cost. Therefore, the extruder should be consulted during the design process to ensure producibility, dimensional control, and finish capabilities that are required for the application.

Producibility is limited by metal-flow characteristics and is a function of alloy composition, extrusion temperature, press size, and shape complexity. Shapes are classified with respect to producibility into solid, hollow, and semihollow types and further classified by rules based on the dimensions of the features. The difficulty of extrusion can be estimated from the dimensions, taking into account the alloy to be extruded.

The overall size of the shape affects ease of extrusion and dimensional tolerances. As the circumscribing circle size (smallest diameter that completely encloses the shapes; see Fig. 5) increases, extrusion becomes more difficult. Metal flow is most rapid at the center of the die face. As circle size increases, differences in flow rate from the center to the outside of the shape increase, and die design and construction to counteract this effect are more difficult.

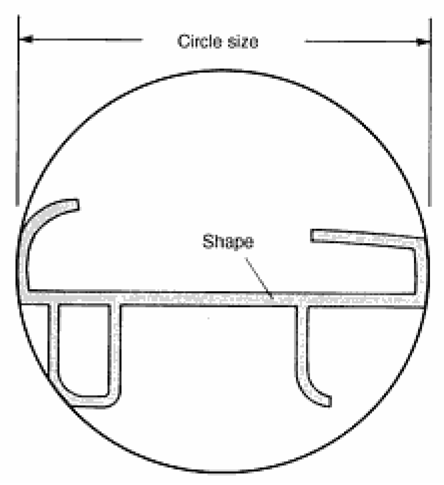


Fig. 5 Illustration of circumscribing circle method of characterizing the size of an extruded shape

Complexity and production difficulty also increase with increasing "shape factor," which is the ratio of the perimeter of a shape to its weight per unit length. Increasing thickness aids extrusion, and shapes having uniform thickness are most easily extruded. Although weight and metal cost decrease with decreasing thickness, the increasing extrusion cost may offset the savings in metal cost. Limits on minimum practical thickness, which depend on circle size, classification, and alloy, are given in Table 2.

Table 2 Standard manufacturing limits (in inches) for aluminum extrusions

Diameter of circumscribing circle, in.	Minimum wall thickness, in.				
	1060, 1100, 3003	**6063**	**6061**	**2014, 5086, 5454**	**2024, 2219, 5083, 7001, 7075, 7079, 7178**
Solid and semihollow shapes, rod and bar					
0.5-2	0.040	0.040	0.040	0.040	0.040
2-3	0.045	0.045	0.045	0.050	0.050
3-4	0.050	0.050	0.050	0.050	0.062
4-5	0.062	0.062	0.062	0.062	0.078

5-6	0.062	0.062	0.062	0.078	0.094
6-7	0.078	0.078	0.078	0.094	0.109
7-8	0.094	0.094	0.094	0.109	0.125
8-10	0.109	0.109	0.109	0.125	0.156
10-11	0.125	0.125	0.125	0.125	0.156
11-12	0.156	0.156	0.156	0.156	0.156
12-17	0.188	0.188	0.188	0.188	0.188
17-20	0.188	0.188	0.188	0.188	0.250
20-24	0.188	0.188	0.188	0.250	0.500
Class 1 hollow shapes(a)					
1.25-3	0.062	0.050	0.062	. . .	. . .
3-4	0.094	0.050	0.062	. . .	. . .
4-5	0.109	0.062	0.062	0.156	0.250
5-6	0.125	0.062	0.078	0.188	0.281
6-7	0.156	0.078	0.094	0.219	0.312
7-8	0.188	0.094	0.125	0.250	0.375
8-9	0.219	0.125	0.156	0.281	0.438
9-10	0.250	0.156	0.188	0.312	0.500
10-12.75	0.312	0.188	0.219	0.375	0.500
12.75-14	0.375	0.219	0.250	0.438	0.500
14-16	0.438	0.250	0.375	0.438	0.500

16-20.25	0.500	0.375	0.438	0.500	0.625
Class 2 and 3 hollow shapes(b)					
0.5-1	0.062	0.050	0.062	. . .	. . .
1-2	0.062	0.055	0.062	. . .	. . .
2-3	0.078	0.062	0.078	. . .	. . .
3-4	0.094	0.078	0.094	. . .	. . .
4-5	0.109	0.094	0.109	. . .	. . .
5-6	0.125	0.109	0.125	. . .	. . .
6-7	0.156	0.125	0.156	. . .	. . .
7-8	0.188	0.156	0.188	. . .	. . .
8-10	0.250	0.188	0.250	. . .	. . .

(a) Minimum inside diameter is one-half the circumscribing diameter, but never under 1 in. for alloys in first three columns or under 2 in. for alloys in last two columns.

(b) Minimum hole size for all alloys is 0.110 $in.^2$ in area of 0.375 in. in diam.

Alloy selection for extruded shapes has an important effect on producibility and cost as well as on minimum thickness. The extrusion speed possible for a given shape is strongly affected by the composition being extruded and may vary by as much as a factor of 20 (see Table 3).

Table 3 Relative extrudability of aluminum alloys

Alloy	Extrudability, % of rate for alloy 6063
1350	160
1060	135
1100	135

3003	120
6063	100
6061	60
2011	35
5086	25
2014	20
5083	20
2024	15
7075	9
7178	8

Forgings

The term "hand forgings" is applied to most of the open-die forgings produced on flat or contoured dies generally in hydraulic presses with capacities up to 445 MN (50,000 tonf). The most usual are of rectangular or cylindrical cross section and may be produced in economical lengths (multiple length) and later cut into shorter pieces. The general category includes disk-shape parts sometimes referred to as "biscuits" as well as more complicated pieces that may vary in cross section through the length or be bent, curved, or contoured. These forgings fill a frequent need in which the number of pieces required does not justify the time and expense of impression dies. Mandrel-forged rings are another type of open-die-forged product.

Forgings of all types, produced on hammers, mechanical presses, or hydraulic presses, range in size from 45 g (0.1 lb) to 1360 kg (3000 lb) or over. Those weighing up to 450 kg (1000 lb) are produced regularly, those weighing between 450 and 900 kg (1000 and 2000 lb) are less common, and pieces weighing more than 900 kg are special items.

Most aluminum forgings are produced in closed dies and can vary widely in detail and closeness of approach to the final dimensions desired. The ultimate in shaping parts by forging is represented by "precision forgings," which are essentially net-shape parts requiring little or no machining. The advantage of closed-die forgings is that the metallurgical-structure alignment follows the part contours. This is sometimes called the "grain-flow pattern." This alignment is highly favorable for static strength and fatigue resistance (refer to Fig. 3 and 4). In working operations preliminary to final shaping, the metal may be upset and drawn in ways that further improve final mechanical properties.

Particularly for die forgings, which represent engineered products designed to perform specific functions in specific machines or vehicles, the choice of forging process and tooling must be approached on a cost-effective basis involving quantities needed, tooling, forging, and machining costs, and the net effects of these factors. There are great variations in this problem, from the extreme case of simple parts for which tooling costs are inconsequential to parts ordered in large quantities, which usually justify the tooling cost of dies to produce a part with conventional machining allowances or even the higher initial costs of precision forging.

The alloy used affects costs, reflecting the relative alloy forgeability (see Fig. 6). This factor, combined with those discussed in the preceding paragraph, may account for a price ratio of up to 10 to 1 for parts of the same weight. Forgings dies are more expensive than extrusion dies by a factor varying from the ratio 4 to 1 to the ratio 3 to 1, for small and large sections. Factors in formulating decisions as to whether parts should be shaped by machining from bar or plate stock or be produced as hand or die forgings are considered in the section of this article "Product Economics, Selection, and Design." In many cases, a die forging may serve to replace an assembly of parts produced from mill products and stampings or shapes.

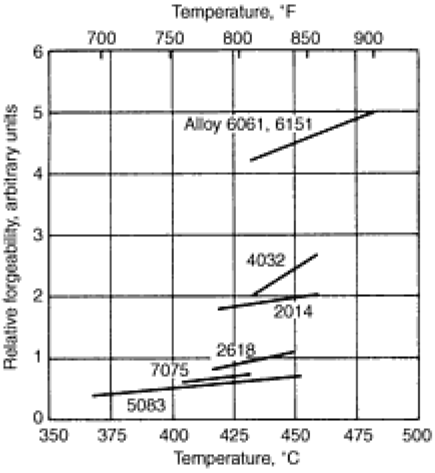


Fig. 6 Forgeability vs forging temperature for seven aluminum alloys. Forgeability increases as the arbitrary unit increases.

The alloys most prominent in forgings are of the 2*xxx*, 6*xxx*, and 7*xxx* types; 1*xxx*, 3*xxx*, 4*xxx*, and 5*xxx* are producible but are used with less frequency (see Table 1). Limitations on controlled strain-hardening capability and on use of strain to produce T8-type tempers influence the use of some of these alloys. The largest forging tonnages in markets other than aerospace are accounted for by automobile and truck wheels of alloy 6061, whereas the aerospace industry uses forgings principally of 2*xxx* and 7*xxx* alloys (2014, 2219, 7049, 7050, 7075, and 7175).

Mandrel-forged or ring-rolled rings are produced in some forging plants. More information on a variety of representative die forgings, including the alloys and tempers used, the types of forging equipment used, and comments on selection factors, is given in Volume 14, *Forming and Forging,* of the *ASM Handbook.*

Impacts

Impacts are formed in a confining die from a lubricated slug, usually cold, by a single-stroke application of force through a metal punch, causing the metal to flow around the punch or die. The process lends itself to high production rates, with precision parts being produced to exacting quality standards. Impacts involve a combination of cold extrusion and cold forging and, as such, combine most of the advantages of both the forging and extrusion processes. Impacts usually have properties in the longitudinal direction equal to those specified for other product forms of similar composition.

There are three basic types of impacting, all of which are used on aluminum. Reverse impacting is used to make shells with forged bases and extruded sidewalls. The slug is placed in a die cavity and struck by a punch, which forces the metal to flow back (upward) around the punch, and then through the opening between the punch and die, to form a simple shell. Forward impacting somewhat resembles conventional extrusion in that the metal is forced through an orifice in the die by the action of a punch, causing the metal to flow in the direction of punch travel. The punch fits the walls of the die so closely that no metal escapes backwards. Forward impacting with a flat-face punch is used to form round, nonround, straight, and ribbed rods, and forward impacting with a stop-face punch is used to form thin-wall tubes with one or both ends open, and with parallel or tapered sidewalls. If the punch is smaller than the die and the die contains an orifice, reverse and forward impacting can be combined to produce a combination impact.

A major consideration in designing aluminum impacts is selection of the appropriate alloy. Alloys 1100, 2014, 3003, 6061, 6351, and 7075 are most often utilized in aluminum impacts. These alloys offer a range of mechanical properties that fits most applications. Generally, the stronger the alloy impacted is, the shorter the tool life and the higher the production costs. Although each part must be considered individually, the stronger alloys generally require greater minimum wall thicknesses.

Alloy 1100, which has excellent corrosion resistance in rural, industrial, and marine atmospheres, is commonly impacted to form containers for liquid and semiliquid materials such as food preserves and products sprayed by aerosols. Alloy 3003 is used for many of the same applications as alloy 1100, but it is selected when higher strength than that of 1100 is required. Alloy 6061, which is heat treatable and has excellent corrosion resistance, is widely used in the manufacture of parts for automotive, aircraft, and marine applications, especially where welding is involved or high strength is required. Alloy 6351 is a medium-to-high-strength heat treatable alloy with good corrosion resistance. Alloy 2014 is a heat treatable alloy used for general applications where high tensile and yield strengths, combined with good ductility and good fatigue resistance, are essential. It is widely used in structural applications and in aircraft, automobile, and ordnance parts. Alloy 7075 has the highest strength and hardness of these alloys. This heat treatable alloy is used for many of the same applications as those of alloy 2014, but it is selected where highest stresses are expected or for maximum weight savings.

Other Mill Products

Fin stock is coiled sheet or foil in specific alloys, tempers, and thickness ranges suitable for manufacture of fins for heat-exchanger applications. As shown in Table 1, commonly used alloys include 1100, 1145, 3003, 7072.

Alclad Products. As described earlier, aluminum products sometimes are coated on one or both surfaces with a metallurgically bonded, thin layer of pure aluminum or aluminum alloy. If the combination of core and cladding alloys is selected so that the cladding is anodic to the core, it is called *alclad*. The cladding of alclad products electrochemically protects the core at exposed edges and at abraded or corroded areas. When a corrosive solution is in contact with the product, current from the anodic cladding flows through the electrolyte to the cathodic core, and the cladding tends to dissolve preferentially, thus protecting the core. Sustained protection is dependent on obtaining the optimum quantity of current (which is influenced by the potential difference between the cladding and core), the conductivity of the corroding medium, film formation, and polarization (see the article "Corrosion Resistance of Aluminum and Aluminum Alloys" in this Section).

The corrosion potentials of cladding and core alloys are important in selecting a coating that is sufficiently anodic to electrochemically protect the core. Copper in solid solution in aluminum is less anodic as copper content increases. Consequently, pure aluminum is anodic to aluminum-copper-magnesium alloys in the naturally aged T3*x* and T4*x* tempers by about 0.154 V and is used as the cladding for most alclad 2*xxx* products. Increasing zinc in solid solution increases the anodic potential of aluminum alloys, while Mg_2Si and manganese have little effect. Alloy 7072, Al-1Zn, has a more anodic potential than pure aluminum and is used as the cladding for Alclad 3003, 5052, 6061, and 7075, as well as others.

The most widely used alclad products are sheet and plate, although wire, tube, and other forms are also produced. The most generally accepted method of fabricating alclad sheet and plate consists of hot rolling to pressure weld the cladding slabs to a scalped core ingot. In fabricating alclad products, the temperature and time of thermal treatments should be minimized to avoid extensive diffusion of soluble elements from the core. This is particularly important in the 2*xxx* alloys, as diffusion of copper in the cladding makes it less anodic. It is less important in alloys containing zinc and magnesium, because these elements make the cladding more anodic.

The percentage of cladding thickness is determined principally by the thickness of the finished part. Because the objective is to provide an adequate absolute thickness, the percentage of thicker parts need not be as great as the percentage for thinner parts. A listing of the most widely used alclad products is given in Table 4.

Table 4 Components of clad products

Designation	Component alloys(a)		Total specified thickness of composite product, in.	Sides clad	Cladding thickness per side, % composite thickness		
					Nominal	**Average(b)**	
	Core	**Cladding**				**min**	**max**
Alclad 2014 sheet and plate	2014	6003	≤0.024	Both	10	8	. . .
			0.025-0.039	Both	7.5	6	. . .
			0.040-0.099	Both	5	4	. . .
			≥0.100	Both	2.5	2	3(c)
Alclad 2024 sheet and plate	2024	1230	≤0.062	Both	5	4	. . .
			≥0.063	Both	2.5	2	3(c)
$1\frac{1}{2}$ % Alclad 2024 sheet and plate	2024	1230	≥0.188	Both	1.5	1.2	3(c)
Alclad one side 2024 sheet and plate	2024	1230	≤0.062	One	5	4	. . .
			≥0.063	One	2.5	2	3(c)
$1\frac{1}{2}$ % Alclad one side 2024 sheet and plate	2024	1230	≥0.188	One	1.5	1.2	3(c)
Alclad 2219 sheet and plate	2219	7072	≤0.039	Both	10	8	. . .
			0.040-0.099	Both	5	4	. . .
			≥0.100	Both	2.5	2	3(c)
Alclad 3003 sheet and plate	3003	7072	All	Both	5	4	6(c)
Alclad 3003 tube	3003	7072	All	Inside	10	. . .	. . .
			All	Outside	7	. . .	. . .

Alclad 3004 sheet and plate	3004	7072	All	Both	5	4	6(c)
Alclad 5056 rod and wire	5056	6253	$\leq$0.375	Outside	20	16	
					(of total cross-sectional area)		
Alclad 6061 sheet and plate	6061	7072	All	Both	5	4	6(c)
Alclad 7050 sheet and plate	7050	7072	$\leq$0.062	Both	4	3.2	. . .
			$\geq$0.063	Both	2.5	2	. . .
7108 Alclad 7050 sheet and plate	7050	7108	$\leq$0.062	Both	4	3.2	. . .
			$\geq$0.063	Both	2.5	2	. . .
Alclad 7075 sheet and plate	7075	7072	$\leq$0.062	Both	4	3.2	. . .
			0.063-0.187	Both	2.5	2	. . .
			$\geq$0.188	Both	1.5	1.2	3(c)
$2\frac{1}{2}$ % Alclad 7075 sheet and plate	7075	7072	$\geq$0.188	Both	2.5	2	4(c)
Alclad one side 7075 sheet and plate	7075	7072	$\leq$0.062	One	4	3.2	. . .
			0.063-0.187	One	2.5	2	. . .
			$\geq$0.188	One	1.5	1.2	3(c)
$2\frac{1}{2}$ % Alclad one side 7075 sheet and plate	7075	7072	$\geq$0.188	One	2.5	2	4(c)
7008 Alclad 7075 sheet and plate	7075	7008	$\leq$0.062	Both	4	3.2	. . .
			0.063-0.187	Both	2.5	2	. . .
			$\geq$0.188	Both	1.5	1.2	3(c)

7011 Alclad 7075 sheet and plate	7075	7011	≤0.062	Both	4	3.2	. . .
			0.063-0.187	Both	2.5	2	. . .
			≥0.188	Both	1.5	1.2	3(c)
Alclad 7178 sheet and plate	7178	7072	≤0.062	Both	4	3.2	. . .
			0.063-0.187	Both	2.5	2	. . .
			≥0.188	Both	1.5	1.2	3(c)
Alclad 7475 sheet	7475	7072	≤0.062	Both	4	3.2	. . .
			0.063-0.187	Both	2.5	2	. . .
			0.188-0.249	Both	1.5	1.2	. . .
No. 7 brazing sheet	3003	4004	≤0.024	One	15	12	18
			0.025-0.062	One	10	8	12
			≥0.063	One	7.5	6	9
No. 8 brazing sheet	3003	4004	≤0.024	Both	15	12	18
			0.025-0.062	Both	10	8	12
			≥0.063	Both	7.5	6	9
No. 11 brazing sheet	3003	4343(d)	≤0.063	One	10	8	12
			≥0.064	One	5	4	6
No. 12 brazing sheet	3003	4343(d)	≤0.063	Both	10	8	12
			≥0.064	Both	5	4	6
No. 23 brazing sheet	6951	4045	≤0.090	One	10	8	12

			≥0.091	One	5	4	6
No. 24 brazing sheet	6951	4045	≤0.090	Both	10	8	12
			≥0.091	Both	5	4	6
Clad 1100 reflector sheet	1100	1175	≤0.064	Both	15	12	18
			≥0.065	Both	7.5	6	9
Clad 3003 reflector sheet	3003	1175	≤0.064	Both	15	12	18
			≥0.065	Both	7.5	6	9

(a) Cladding composition is applicable only to the aluminum or aluminum alloy bonded to the alloy ingot or slab preparatory to processing to the specified composite product. The composition of the cladding may be subsequently altered by diffusion between the core and cladding due to thermal treatment.

(b) Average thickness per side as determined by averaging cladding thickness measurements taken at a magnification of 100 diameters on the cross section of a transverse sample polished and etched for microscopic examination.

(c) Applicable for thicknesses of 0.500 in. and greater.

(d) The cladding component, in lieu of 4343 alloy, may be 5% 1*xxx* clad 4343.

Specialty mill products include brazing sheet, corrugated sheet for roofing and siding, and heat-exchanger tubing. These and other specialty mill products are listed in Table 5.

Table 5 Specialty mill products

Specialty product designation	Specialty-product description		Temper
	Form	**Alloy**	
Brazing sheet			
No. 11 and 12	Sheet	3003 clad with 4343 on one side (No. 11) or on both sides (No. 12)	O, H12, H14
No. 23 and 24	Sheet	6951 clad with 4045 on one side (No. 23) or on both sides (No. 24)	O

Reflector sheet			
Clad 1100	Sheet	1100 clad with 1175 on one or both sides	. . .
Clad 3003	Sheet	3003 clad with 1175 on one or both sides	. . .
Painted sheet	Coiled sheet	1100, 3003	O, H12, H14, H16, H18
	Coiled sheet	3105	O, H12, H14, H16, H18, H25
	Coiled sheet	5005, 5050, 5052	O, H32, H34, H36, H38
Commercial roofing and siding			
Corrugated roofing and siding	Sheet	3004, Alclad 3004	. . .
V-beam roofing and siding	Sheet	3004, Alclad 3004	. . .
Ribbed roofing	Sheet	Alclad 3004	. . .
Ribbed siding	Sheet	3004, Alclad 3004	. . .
Duct sheet	Coiled or flat sheet	Alloy and temper with minimum tensile strength of 16.0 ksi	. . .
Tread plate	Sheet and plate with raised pattern on one surface	6061	O, T4, T6
Heat-exchanger tube	Tube	1060	H14
		3003	H14, H25
		Alclad 3003	H14, H25
		5052	H32, H34
		5454	H32, H34

		6061	T4, T6
Rigid electrical conduit	Tube	3003	H12
		6063	T1

Product Economics, Selection, and Design

In the "cost-effective" approach to the problem of material selection, the only valid basis for choosing a particular material is that it will perform all required functions at the lowest overall cost. The material chosen may be the most cost-effective because (a) it is lowest in first cost and provides service and durability at least equal to those offered by any alternative material; (b) it is most economical in the long run due to lowest operating or maintenance costs; or (c) it has special characteristics not matched by any alternative material. These considerations at times are "warped" by artificial factors arising from such sources as legislation or the "energy crisis." Also, they may at times be greatly influenced, or even outweighed, by factors of availability or delivery time.

The choice between aluminum and some other material on the cost-effective basis is sometimes simple and at other times quite complex; in these cases the choice may shift from one time to another as relative costs change. Machining, joining, or finishing capabilities, as well as physical properties (predominantly density, conductivity, or reflectivity), are foremost considerations in many cases. The competitive position of aluminum in this race is often greatly augmented by the myriad design possibilities offered by aluminum shapes and forged parts. (Aluminum engineered castings also offer many of these advantages.)

Product selection is based primarily on shape, dimensional, and mechanical requirements. The piece needed may be required to cover or enclose an area, to fill a certain space, to connect or attach to other pieces, or to conduct or contain a fluid or gas, or it may be limited by weight or other factors. There is seldom any question concerning the best choice in the case of products like foil, wire, tube, or large-area applications for sheet. In other cases, an intelligent choice from among the various products is a complex engineering problem involving many factors in addition to first cost of the product itself. Shapes or die forgings frequently offer the advantage of a single piece having such features as ribs for stiffening, fins for heat dissipation, and bosses or pads for attachment, replacing several pieces that must be cut, formed, and joined. Mechanical-property considerations may be important in some cases, that is such matters as the availability or unavailability of an alloy and temper in a particular product type, the higher longitudinal static strength of extruded versus rolled or forged products, or the matching of metallurgical-structure alignment (or grain-flow pattern) with surface contours, a matter that is characteristic of die forgings.

For the most stringent structural applications, the greatest hazards are those posed by dynamic stresses and by combinations of static stresses from assembly interferences or misfits with dynamic applied stresses and corrosive environments. To avoid premature failure from fatigue cracking or stress-corrosion cracking, good mechanical design to minimize such stresses, stress concentrations and exposure to and entrapment of corrosive media are of paramount importance. The type of product and the alloy and temper selected also play a strong role in the design process.

Product Dimensions and Dimensional Tolerances

The ranges of thickness in which foil, sheet, and plate are available were stated previously. By definition, foil is no greater than 0.15 mm (0.006 in.) thick and for some purposes is as thin as 0.0043 mm (0.00017 in.), sheet ranges from over 0.15 to 6.3 mm (over 0.006 to 0.249 in.) thick, and plate ranges from 6.3 to ~200 mm (0.250 to ~8 in.) thick. Corresponding width, length, and coil-size limitations are matters for inquiry with producers.

Standard dimensional tolerances for all mill products are contained in the American National Standard Institute document H35.2-1993, Annual Book of *ASTM Standards,* Volume 02.02 and in the Aluminum Association publication *Aluminum Standards and Data.* These dimensional tolerances on thickness, width, length, diameter, squareness, flatness, straightness, lateral bow, and twist, as applicable, vary with product type and are not tabulated in this Handbook.

The limiting dimensions for extruded products, including rod and bar, and for other solid, hollow, and semihollow shapes, with respect to maximum circumscribing circle size and minimum wall thickness, are alloy dependent, as indicated in Table 2. Various sizes of structural shapes (angles, channels, I-beams, H-beams, Tees, and Zees) produced from alloy 6061-T6 have been established as standard products by the Aluminum Association. Detailed dimensions, weights per lineal foot, and section properties (moment of inertia, section modulus, and radius of gyration) for these standard structural shapes--data which are useful for design--are also tabulated in the Aluminum Association publication *Aluminum Standards and Data.* These data, as well as those given in the same publication for standard pipe sizes, are not repeated in this Handbook.

Limiting dimensions in design of die forgings include total plan area, which may be as great as ~0.3 m^2 (~500 $in.^2$) for forgings produced in mechanical presses, ~1.9 m^2 (~3000 $in.^2$) for hammer forgings, and ~3.2 m^2 (~5000 $in.^2$) for parts made in the largest hydraulic presses. Other limiting design features are web thickness, rib thickness and height, draft angles, and minimum radii for fillets and corners.

Cylindrical and other axisymmetric shapes are easiest to produce as impacts, but nonsymmetrical shapes may also be produced. Longitudinal ribs can be incorporated in sidewalls, either inside or outside. Lugs, bosses, grooves, depressions, and even ribs can be incorporated in the end or base configuration. Dimensional limitations apply to maximum diameter (dependent on press size), length-to-diameter ratio (a maximum of 18 to 1, with 12 to 1 more normal), and minimum wall thickness. All of these shape factors are alloy dependent.

Effective Design and Use of Wrought Product Capabilities

Good design for aluminum can be defined as making the most effective use of its capabilities. An outstanding example of this is the two-piece all-aluminum beverage container. Thin, coiled sheet of relatively high-strength alloys (3004 for the can body; 5182 for the lid), rolled at extremely high speeds, is drawn and ironed to produce the body and formed to produce easy-open ends. Both of these manufacturing operations produce the parts at extremely high rates. The favorable economics of lowest first cost, lower shipping costs (because of low weight), and recyclability combine with functional advantages to make these containers a viable and successful product in a highly competitive market. Such containers are pressure vessels in addition to being subject to considerable abuse from handling, and these factors require the best possible balance among alloy strength, fabricability, and design. Tool design for production of these containers played a key role in making them successful.

Roofing and siding for highway freight trailers represent another highly effective, high-volume use of aluminum alloy sheet with advantages in both first and lifetime costs. These applications employ semi-monocoque (stressed skin) construction and moderately high-strength, non-heat-treatable alloys. Skins for aircraft wings, control surfaces, and fuselages (pressure vessels) are likewise effective in both cost and function. These applications employ high-strength, heat treatable alloys, and forming operations ranging from mild to severe. In some cases, the good formability of freshly quenched, very long wing-skin panels is preserved by refrigeration during transcontinental shipment by rail in special cars from mill to aircraft factory. The fact that sheet accounts for such a high percentage of all aluminum mill products produced and shipped annually (nearly 60% in 1996) attests to the versatility and high efficiency of this form in a myriad of applications.

Plate is an obvious selection for many purposes. One example is large welded storage tanks used on space vehicles with formed and welded plate members serving the dual function of containing the fuel and oxidizers (cryogenic liquids) as well as forming the structure of the vehicle. For such applications, as well as for aircraft wings, plate may be extensively machined or chemically milled to form integral stiffening ribs or waffle patterns. When only longitudinal stiffening ribs are required, an alternative product is wide extruded panels with integral ribs.

For some designs, machining may be the most economical production technique, because the setup time may account for a large part of the cost of machining. In Fig. 7, for instance, the machined plate was the least expensive method of producing the aluminum part until production reached 600 pieces. At that point, the quantity was sufficient to compensate for the cost of the extrusion die. The built-up design, with skin on both surfaces, was heavier and costlier.

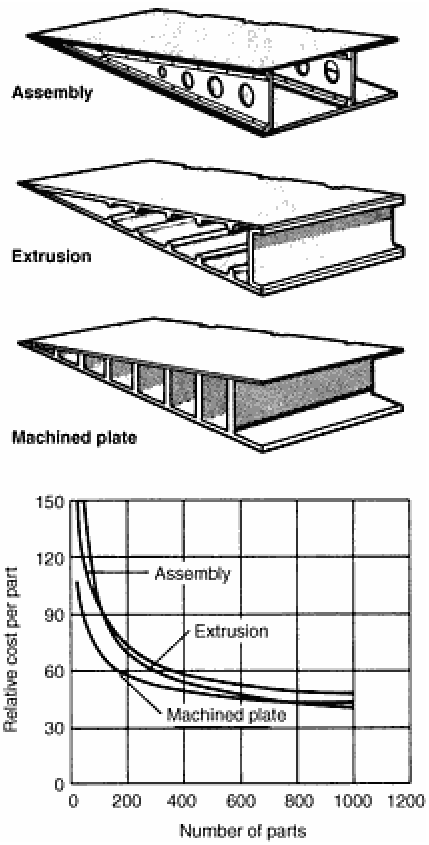


Fig. 7 Cost comparison for producing an alloy 2024-T4 part by three methods

Chemical milling (removal of metal by dissolution in an alkaline or acid solution) is routine for specialized operations on aluminum. For flat parts on which large areas having complex or wavy peripheral outlines are to be reduced only slightly in thickness, chemical milling is usually the most economical method.

For sheet metal parts that cannot be formed after machining, chemical milling is the only practical method by which metal can be removed to obtain a waffle-type grid with uniform skin thickness. Even then, allowance must often be made for some springback resulting from metal removal and the consequent redistribution of residual forming stresses.

Chemical milling can normally produce a stiffened skin to a thickness tolerance of ±0.13 mm (±0.005 in.), with the cladding left intact on the unmilled surface. Mechanical milling of skins from sheet thicker than 3 mm ($\frac{1}{8}$ in.) requires a cleanup "skim" cut for flatness on the hold-down surface, because of hold-down limitations.

Extruded Shapes. Extrusions, with their great design versatility, good surface quality, and precise dimensions, frequently do not have to be machined extensively; the configuration and dimensional precision of the as-extruded product often permits a manufacturer to complete the part by simple cutoff, drilling, broaching, or other minor machining operations. For any part that can be produced as an extrusion, the cost of the extrusion die is usually written off after a few parts have been produced.

Cost of machining may be the only selection consideration. This is illustrated in Fig. 8 by the cost figures for a fuel-tank attachment fitting. The design of this part permitted the use of an extrusion, which required very little machining compared with the same part fabricated from solid bar. After about 100 pieces, the cost per piece decreased substantially.

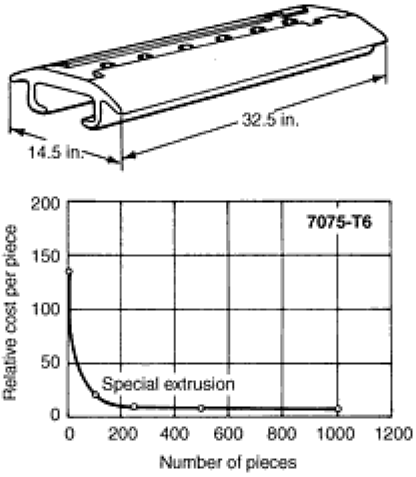


Fig. 8 Cost of an extruded fuel-tank attachment fitting as a function of quantity. A part completely machined from bar stock is rated 100.

Interconnecting Shapes. It is becoming increasingly common to include an interconnecting feature in the design of an extruded shape to facilitate its assembly to a similar shape or to another product. It can be a simple step to provide a smooth lapping joint or a tongue and groove for a nesting joint (see Fig. 9). Such connections can be secured by any of the common joining methods. Of special interest when the joint is to be arc welded is the fact that lapping and nesting types of interconnections can be designed to provide edge preparation and/or integral backing for the weld (see sketch at bottom right in Fig. 9).

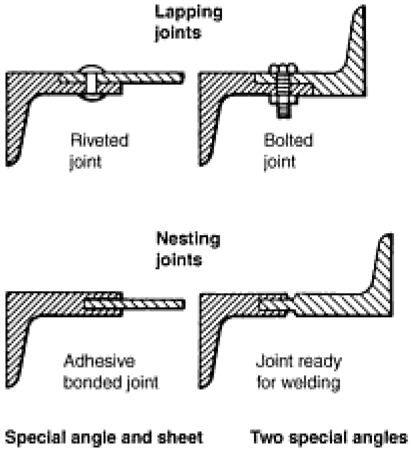
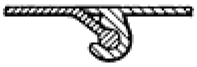
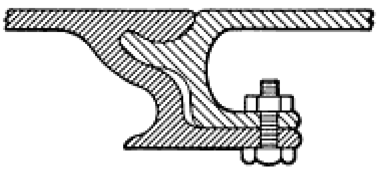

Lapping joints
Riveted joint
Bolted joint
Nesting joints
Adhesive bonded joint
Joint ready for welding
Special angle and sheet
Two special angles

Fig. 9 Four examples of interconnecting extrusions that fit together or fit other products, and four examples of joining methods

Interlocking joints can be designed to incorporate a free-moving hinge (see top sketch in Fig. 10) when one part is slid lengthwise into the mating portion of the next. Panel-type extrusions with hinge joints have found application in conveyor belts and roll-up doors.



Free-moving hinge

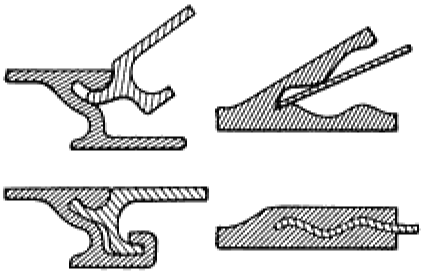


Bolt-lock

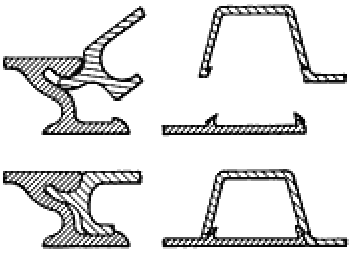
Fig. 10 Two examples of extrusions with nonpermanent interconnections

A more common type of interlocking feature used in interconnecting extrusions is the nesting type that requires rotation of one part relative to the mating part for assembly (see bottom sketch in Fig. 10). Such joints can be held together by gravity or by mechanical devices. If a nonpermanent joint is desired, a bolt or other fastener can be used, as illustrated in the bottom sketch in Fig. 10.

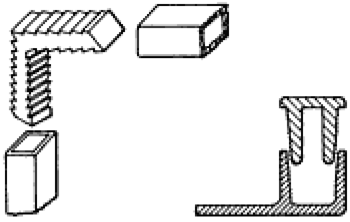
When a permanent joint is desired, a snapping or crimping feature can be added to interlocking extrusions (see Fig. 11). Crimping also can be used to make a permanent joint between an interlocking extrusion and sheet (Fig. 11). Extrusions also can be provided with longitudinal teeth or serrations, which will permanently grip smooth surfaces as well as surfaces provided with mating teeth or serrations; this is illustrated in the sketch at the bottom of Fig. 11.



Crimped joints



Snap joints



Toothed or
serrated joints

Fig. 11 Six examples of interconnecting extrusions that lock together or lock to other products

Applications for interconnecting extrusions include doors; wall, ceiling, and floor panels; pallets; aircraft landing mats; highway signs; window frames; and large cylinders.

Die Forgings. The diversity of geometrical possibilities offered by aluminum die forgings frequently makes them highly advantageous choices in that they can be produced without costly machining, joining, or assembly operations. When compared with alternative methods of achieving the same functions, the integral product is often ahead in a value analysis. Tool (die) costs play a major role in the decision when the choice is between machining parts from bar or plate stock and purchasing die forgings. In other cases, the differences in directionality of wrought structure of the different products, which affect expected resistance to directional stresses and service environments, may be the principal deciding factor.

The cost of machining a few parts from a bar or slab is usually less than the cost of making a die and producing the parts by forging. When greater numbers of parts are to be produced, forging usually is the less-expensive method. In borderline cases, a detailed study of machining and die costs is necessary to determine the crossover point. In determining this point, it is necessary to calculate only the original cost of the die, because the supplier of the forging is responsible for die replacements caused by breakage or wear. This replacement cost is included in the price of the forgings. Die cost varies with the size and intricacy of the part.

In Fig. 12, a die forging (part A) is compared with a built-up design. Although 75% of the metal was machined away from the rough forging, the machined forging was more economical than the assembly for quantities greater than 125.

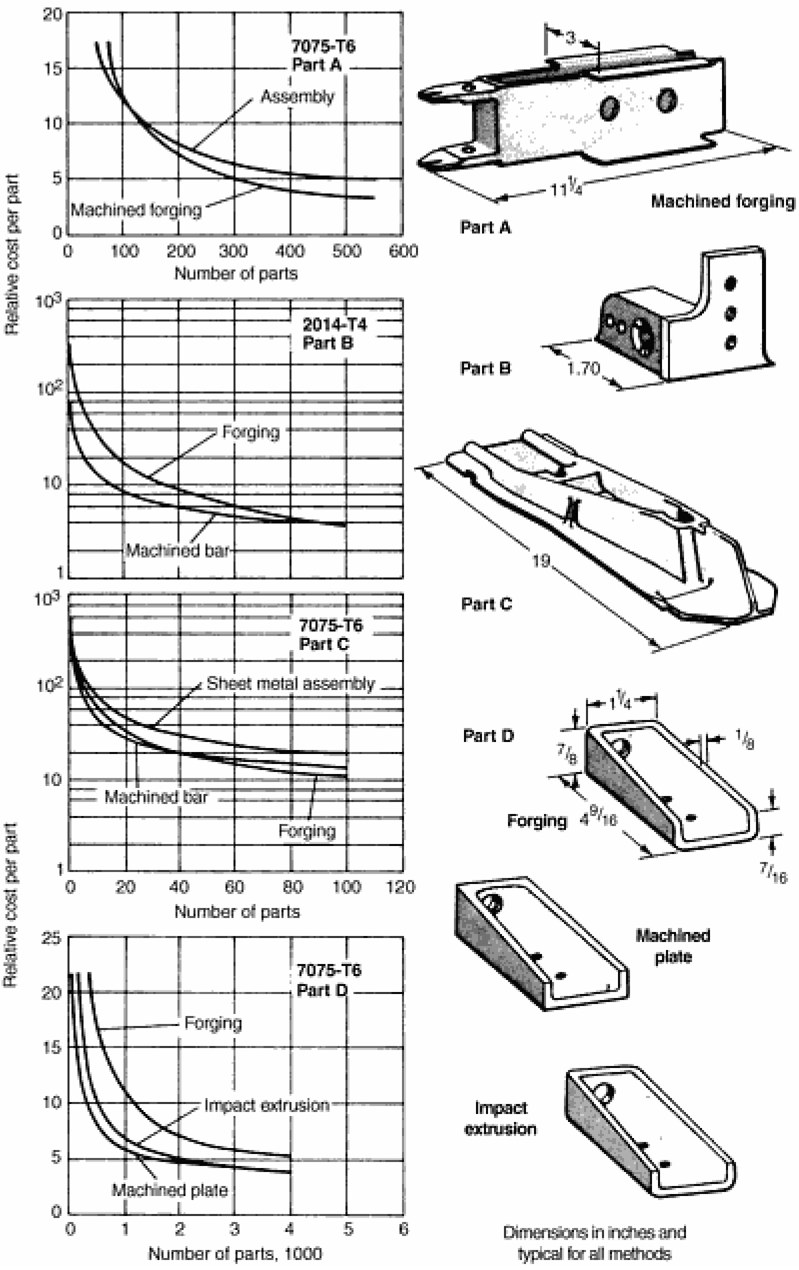


Fig. 12 Relative costs of aluminum die forgings and similar components fabricated by other methods. The comparison for Part A is between a built-up design and a die forging. Although the rough forging was machined on all surfaces, a saving in fabrication cost was evident after about 125 forged fittings had been made. Part B is a simpler part, and the costs of forging compared with machining from bar were the same at about the 100th piece. For a more complicated forging (part C), the crossover point where the machined bar became more expensive than the forging occurred at 40 pieces. Part D, a relatively simple fitting, was made as a die forging, an impact extrusion, and a hollowed-out fitting. Forging was the most expensive approach. The cost of extrusion and of machining from plate were about the same for 3000 fittings.

In some large, complicated forgings, the break-even point may be at the first or second forging. It also may be desirable to rough forge the part in relatively inexpensive roughing dies and complete the part by machining if only a few pieces are desired. When this technique is used, the desirable flow of metal induced by forging and the consequent improvement in properties can be obtained at a lower cost than would have to be paid for a part forged to final dimensions.

The curves in Fig. 12 compare costs of parts of different size and shape, produced by competitive methods. For the simpler part, B, the crossover point occurs at about 100 pieces. For the complicated forging (part C), the crossover point occurs at 40 pieces. The items considered in determining the costs of these two parts include fabrication-shop learning curves, unit-run labor, amortized setup, labor, tooling costs (including dies and fixtures), raw materials, and overhead charges.

Die forging is not always the cheapest method of producing a large quantity of parts. A relatively simple fitting (part D in Fig. 12) was analyzed for production costs as a die forging, as an impact extrusion, and as a part machined from plate. The machined fitting was more economical for all quantities, because the cost of the finishing operations required for the die forging closely approached the cost of producing the part by machining only. The thin walls and deep crevices of this fitting should have made it ideally suited to impact extrusion. Analysis showed that this method of manufacture was only slightly more expensive than machining for small quantities and identical in cost for quantities greater than ~3000 parts.

The examples represented by the parts shown in Fig. 12 serve to relate design and cost, and emphasize the necessity for conducting a detailed cost analysis of each of the several methods of fabrication.

Precision Forgings. Precision-forged aluminum alloys are a significant commercial forging product form that has undergone major growth in use and has been the subject of significant technological development and capital investment by the forging industry. Precision aluminum forgings normally require no subsequent machining by the purchaser other than, in some cases, the drilling of attachment holes. They are produced with very thin ribs and webs; sharp corner and fillet radii; undercuts, backdrafts, and/or contours; and frequently, multiple parting planes that may optimize grain flow characteristics.

Selection of precision aluminum forging from the candidate methods of achieving a final aluminum alloy shape is based on value analyses for the individual shape in question. Figure 13 presents a cost comparison for a channel-type aluminum alloy part machined from plate, as-machined from a conventional aluminum forging, and produced as a precision forging; costs as a function of production quantity include application of all material, tooling, setup, and fabrication costs. The break-even point for the precision-forging method versus conventional forging occurs with a quantity of 50 pieces, and when compared to the cost of machining the part from plate, the precision forging is always less expensive. Figure 13 also illustrates the potential cost advantages of precision aluminum alloy forgings. It has generally been found that precision aluminum forgings are highly cost effective when alternate fabrication techniques include multiple-axis machining in order to achieve the final part.

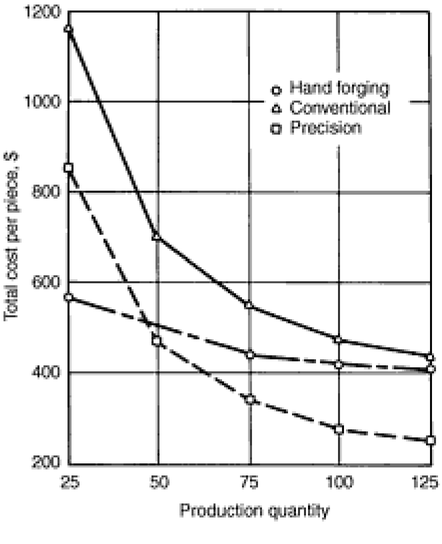


Fig. 13 Cost comparison for the manufacture of an aluminum alloy 7075-T73 component

Recent evaluations by the forging industry and users have shown that precision aluminum forgings can reduce final part costs by up to 80 to 90%, in comparison to machined plate, and 60 to 70%, in comparison to machined conventional forgings. Machining labor can be reduced by up to 90 to 95%.

Specifications for Wrought Mill and Engineered Products

In the United States, specifications and standards for wrought aluminum products are issued/published by ASTM, governmental bodies (military and federal specifications), SAE International (Aerospace Materials Specifications, AMS), the American Society of Mechanical Engineers (ASME), and the American Welding Society (AWS). Table 6 provides a cross reference of the various specifications covering wrought aluminum products.

Table 6 Aluminum mill product specifications

Alloy	Product	Specifications					
		ASTM	**Military**	**Federal**	**AMS**	**ASME**	**AWS**
1060	Sheet and plate	B 209	. . .	. . .	. . .	SB209	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	. . .	. . .	. . .	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	SB221	. . .
	Tube: extruded, seamless	B241	. . .	. . .	. . .	SB241	. . .
	Tube: drawn	B 483	. . .	. . .	. . .	. . .	. . .
	Tube: drawn, seamless	B 210	. . .	. . .	. . .	SB210	. . .
	Tube: condenser	B 234	. . .	. . .	. . .	SB234	. . .
	Pipe: gas and oil transmission	B 345	. . .	. . .	. . .	. . .	. . .
	Tube: condenser with integral fins	B 404	. . .	. . .	. . .	. . .	. . .
1100	Sheet and plate	B 209	. . .	QQ-A-250/1	4001	SB209	. . .
		. . .	. . .	. . .	4003	. . .	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	QQ-A-225/1	4102	. . .	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	SB221	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	SB241	. . .
	Tube: extruded, coiled	B 491	. . .	. . .	. . .	. . .	. . .

	Tube: drawn	B 483	. . .	. . .	. . .	. . .	. . .
	Tube: drawn, seamless	B 210	. . .	WW-T-700/1	4062	. . .	. . .
	Tube: welded	B 313	. . .	. . .	. . .	. . .	. . .
		B 547	. . .	. . .	. . .	. . .	. . .
	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
	Spray gun wire	. . .	MIL-W-6712	. . .	4180	. . .	. . .
	Forgings and forging stock	B 247	. . .	. . .	. . .	. . .	. . .
	Welding rod and electrodes: bare	. . .	. . .	. . .	. . .	A5.10	
	Impacts	. . .	MIL-A-12545	. . .	. . .	. . .	. . .
	Foil	B 479	. . .	QQ-A-1876	. . .	. . .	. . .
1145	Foil	B 373, B 479	. . .	QQ-A-1876	4011	. . .	. . .
1235	Foil	B 373, B 479	. . .	QQ-A-1876	. . .	. . .	. . .
	Tube: extruded, coiled	B 491	. . .	. . .	. . .	. . .	. . .
1350	Aluminum conductors: steel reinforced	B 232	. . .	. . .	. . .	. . .	. . .
		B 401	. . .	. . .	. . .	. . .	. . .
	Bus conductors	B 236	. . .	. . .	. . .	. . .	. . .
	Rolled redraw rod	B 233	. . .	. . .	. . .	. . .	. . .
	Stranded conductors	B 231	. . .	. . .	. . .	. . .	. . .
		B 400	. . .	. . .	. . .	. . .	. . .

	Wire: H19 temper	B 230	. . .	. . .	. . .	. . .	. . .
	Wire: H14 temper	B 609	. . .	. . .	. . .	. . .	. . .
	Wire, rectangular, and square	B 324	. . .	. . .	. . .	. . .	. . .
	Round solid conductor	B 609	. . .				
2011	Tube: drawn, seamless	B 210	. . .	. . .	. . .	. . .	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	QQ-A-225/3	. . .	. . .	. . .
2014	Sheet and plate	B 209	. . .	. . .	4029	. . .	. . .
		. . .	. . .	. . .	4028	. . .	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	QQ-A-225/4	4121	SB 211	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	4153	. . .	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	. . .	. . .
	Tube: drawn, seamless	B 210	. . .	. . .	. . .	. . .	. . .
	Forgings and forging stock	B 247	MIL-A-22771	. . .	4134	SB247	. . .
		. . .	. . .	. . .	4133	. . .	. . .
	Rings: forged and rolled	. . .	. . .	. . .	4314	. . .	. . .
	Impacts	. . .	MIL-A-12545	. . .	. . .	. . .	. . .
Alclad 2014	Sheet and plate	B 209	. . .	QQ-A-250/3	. . .	. . .	. . .
2017	Wire, rod, and bar: rolled or cold finished	B 211	. . .	QQ-A-225/5	4118	. . .	. . .

	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
2018	Forgings and forging stock	B 247	. . .	. . .	4140	. . .	. . .
2024	Sheet and plate	B 209	. . .	QQ-A-250/4	4037	. . .	. . .
		. . .	. . .	. . .	4035	. . .	. . .
		. . .	. . .	. . .	4192	. . .	. . .
		. . .	. . .	. . .	4193	. . .	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	QQ-A-225/6	4112	SB211	. . .
		. . .	. . .	. . .	. . .	. . .	. . .
		. . .	. . .	. . .	4165	. . .	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B221	. . .	. . .	4152	SB221	. . .
		. . .	. . .	. . .	4164	. . .	. . .
		. . .	. . .	. . .	4165	. . .	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	. . .	. . .
	Tube: drawn, seamless	B 210	MIL-T-50777	WW-T-700/3	4087	. . .	. . .
		. . .	. . .	. . .	4088	. . .	. . .
	Tube: hydraulic	. . .	. . .	. . .	4086	. . .	. . .
	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
	Foil	. . .	MIL-A-81596	. . .	. . .	. . .	. . .
Alclad 2024	Sheet and plate	B 209	. . .	QQ-A-250/5	4041	. . .	. . .

		. . .	. . .	. . .	4040	. . .	. . .
		. . .	. . .	. . .	4194	. . .	. . .
		. . .	. . .	. . .	4195	. . .	. . .
Alclad one side 2024	Sheet and plate	. . .	. . .	. . .	4036	. . .	. . .
		. . .	. . .	. . .	4077	. . .	. . .
2025	Forgings and forging stock	B 247	. . .	. . .	4130	. . .	. . .
2117	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
2124	Plate	B 209	. . .	QQ-A-250/29	4101	. . .	. . .
2218	Forgings and forging stock	B 247	. . .	. . .	4142	. . .	. . .
2219	Sheet and plate	B 209	. . .	QQ-A-250/30	4031	. . .	. . .
	Wire, rod, and bar: rolled or cold finished	B211	. . .	. . .	. . .	. . .	. . .
	Wire, rod, bar, profiles (shapes), and tubes: extruded	B 221	. . .	. . .	4162	. . .	. . .
		. . .	. . .	. . .	4163	. . .	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	4068	. . .	. . .
	Tube: drawn, seamless	B 210	. . .	. . .	4066	. . .	. . .
	Forgings and forging stock	B 247	MIL-A-22771	. . .	4143	. . .	. . .
		. . .	. . .	. . .	4144	. . .	. . .
	Armor plate	. . .	MIL-A-46118	. . .	. . .	. . .	. . .
	Rings: rolled on forged	. . .	. . .	. . .	4313	. . .	. . .

	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
Alclad 2219	Sheet and plate	B 209	. . .	. . .	4094	. . .	. . .
		. . .	. . .	. . .	4095	. . .	. . .
		. . .	. . .	. . .	4096	. . .	. . .
2319	Welding rod and electrodes: bare	. . .	. . .	. . .	4191	. . .	A5.10
2618	Forgings and forging stock	B 247	MIL-A-22771	. . .	4132	. . .	. . .
3003	Sheet and plate	B 209	. . .	QQ-A-250/2	4006	SB 209	. . .
		. . .	. . .	. . .	4008	. . .	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	QQ-A-225/2	. . .	. . .	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	SB221	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	SB241	. . .
	Tube: extruded, coiled	B 491	. . .	. . .	. . .	. . .	. . .
	Tube: drawn	B 483	. . .	. . .	. . .	. . .	. . .
	Tube: drawn, seamless	B 210	. . .	WW-T-700/2	4065	SB210	. . .
		. . .	. . .	. . .	4067	. . .	. . .
	Tube: condenser	B 234	. . .	. . .	. . .	SB 234	. . .
	Tube: condenser with integral fins	B 404	. . .	. . .	. . .	. . .	. . .
	Tube: welded	B 313	. . .	. . .	. . .	. . .	. . .
		B 547	. . .	. . .	. . .	. . .	. . .

	Pipe	B 241	MIL-P-25995	. . .	. . .	SB 241	. . .
	Pipe: gas and oil transmission	B 345	. . .	. . .	. . .	. . .	. . .
	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
	Forgings and forging stock	B 247	. . .	. . .	. . .	SB247	. . .
	Foil	. . .	MIL-A-81596	. . .	4010	. . .	. . .
Alclad 3003	Sheet and plate	B 209	. . .	. . .	. . .	SB209	. . .
	Tube: drawn, seamless	B 210	. . .	. . .	. . .	SB210	. . .
	Tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	SB241	. . .
	Tube: condenser	B 234	. . .	. . .	. . .	SB234	. . .
	Tube: condenser with integral fin	B 404	. . .	. . .	. . .	. . .	. . .
	Tube: welded	B 547	. . .	. . .	. . .	. . .	. . .
	Pipe: gas and oil transmission	B 345	. . .	. . .	. . .	. . .	. . .
3004	Sheet and plate	B 209	. . .	. . .	. . .	SB209	. . .
	Tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
	Tube: welded	B 313	. . .	. . .	. . .	. . .	. . .
		B 547	. . .	. . .	. . .	. . .	. . .
Alclad 3004	Sheet and plate	B 209	. . .	. . .	. . .	SB209	. . .
	Tube: welded	B 313	. . .	. . .	. . .	. . .	. . .
		B 547	. . .	. . .	. . .	. . .	. . .

3005	Sheet	B 209	. . .	. . .	. . .	. . .	. . .
3105	Sheet	B 209	. . .	. . .	. . .	. . .	. . .
4032	Forgings and forging stock	B 247	. . .	. . .	. . .	. . .	. . .
4043	Welding rod and electrodes: bare	. . .	. . .	. . .	4190	. . .	A5.10
	Spray gun wire	. . .	MIL-W-6712	. . .	. . .	. . .	. . .
4045	Brazing filler metal	. . .	. . .	. . .	. . .	. . .	. . .
4047	Brazing filler metal	. . .	MIL-B-20148	. . .	4185	. . .	. . .
	Welding rod and electrodes: bare	. . .	. . .	. . .	. . .	. . .	A5.10
4145	Brazing filler metal	. . .	MIL-B-20148	. . .	4184	. . .	. . .
	Welding rod and electrodes: bare	. . .	. . .	. . .	. . .	. . .	A5.10
4343	Brazing filler metal	. . .	. . .	. . .	. . .	. . .	. . .
4643	Welding electrode	. . .	. . .	. . .	4189	. . .	A5.10
5005	Sheet and plate	B 209	. . .	. . .	. . .	. . .	. . .
	Wire: H19 temper	B 396	. . .	. . .	. . .	. . .	. . .
	Stranded conductor	B 397	. . .	. . .	. . .	. . .	. . .
	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
	Rod: rolled	B 531	. . .	. . .	. . .	. . .	. . .
	Tube: drawn, seamless	B 210	. . .	. . .	. . .	. . .	. . .
	Tube: drawn	B 483	. . .	. . .	. . .	. . .	. . .
5050	Sheet and plate	B 209	. . .	. . .	. . .	SB209	. . .

	Tube: drawn, seamless	B 210	. . .	. . .	. . .	. . .	. . .
	Tube: drawn	B 483	. . .	. . .	. . .	. . .	. . .
	Tube: welded	B 313	. . .	. . .	. . .	. . .	. . .
		B 547	. . .	. . .	. . .	. . .	. . .
5052	Sheet and plate	B 209	. . .	QQ-A-250/8	4015	SB209	. . .
		. . .	. . .	. . .	4016	. . .	. . .
		. . .	. . .	. . .	4017	. . .	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	QQ-A-225/7	4114	. . .	. . .
	Tube: drawn	B 483	. . .	. . .	. . .	. . .	. . .
	Tube: drawn, seamless	B 210	. . .	WW-T-700/4	4069, 4070	SB210	. . .
	Tube: hydraulic	. . .	. . .	. . .	4071	. . .	. . .
	Tube: extruded	B221	. . .	. . .	. . .	. . .	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	SB241	. . .
	Tube: condenser	B 234	. . .	. . .	. . .	SB234	. . .
	Tube: condenser with integral fins	B 404	. . .	. . .	. . .	. . .	. . .
	Tube: welded	B313	. . .	. . .	. . .	. . .	. . .
		B547	. . .	. . .	. . .	. . .	. . .
	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
	Foil	. . .	MIL-A-81596	. . .	4004	. . .	. . .

5056	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	. . .	4182	. . .	. . .
	Foil	. . .	MIL-A-81596	. . .	4005	. . .	. . .
Alclad 5056	Wire, rod, and bar: rolled or cold finished	B 211	MIL-C-915	. . .	. . .	. . .	. . .
5083	Sheet and plate	B 209	. . .	QQ-A-250/6	4056	SB209	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	SB221	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	SB241	. . .
	Tube: drawn, seamless	B 210	. . .	. . .	. . .	. . .	. . .
	Tube: welded	B547	. . .	. . .	. . .	. . .	. . .
	Forgings and forging stock	B 247	. . .	. . .	. . .	SB247	. . .
	Pipe: gas and oil transmission	B 345	. . .	. . .	. . .	. . .	. . .
	Armor plate	. . .	MIL-A-46027	. . .	. . .	. . .	. . .
	Extruded armor	. . .	MIL-A-46083	. . .	. . .	. . .	. . .
	Forged armor	. . .	MIL-A-45225	. . .	. . .	. . .	. . .
5086	Sheet and plate	B 209	. . .	QQ-A-250/7	. . .	SB209	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	SB221	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	SB241	. . .
	Tube: drawn, seamless	B 210	. . .	WW-T-	. . .	. . .	. . .

				700/5			
	Tube: welded	B 313	. . .	. . .	. . .	. . .	. . .
		B 547	. . .	. . .	. . .	. . .	. . .
	Pipe: gas and oil transmission	B 345	. . .	. . .	. . .	. . .	. . .
5154	Sheet and plate	B 209	. . .	. . .	. . .	SB209	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	. . .	. . .	SB221	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	SB210	. . .
	Tube: drawn, seamless	B 210	. . .	. . .	. . .	. . .	. . .
	Tube: welded	B 313	. . .	. . .	. . .	. . .	. . .
		B 547	. . .	. . .	. . .	. . .	. . .
5183	Welding rod and electrodes: bare	. . .	. . .	. . .	. . .	. . .	A5.10
5252	Sheet	B 209	. . .	. . .	. . .	. . .	. . .
5254	Sheet and plate	B 209	. . .	. . .	. . .	SB209	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	. . .	. . .
5356	Welding rod and electrodes: bare	. . .	. . .	. . .	. . .	. . .	A5.10
5454	Sheet and plate	B 209	. . .	QQ-A-250/10	. . .	SB209	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	SB221	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	SB241	. . .
	Tube: condenser	B 234	. . .	. . .	. . .	SB234	. . .
	Tube: condenser with integral fins	B 404	. . .	. . .	. . .	. . .	. . .

	Tube: welded	B 547	. . .	. . .	. . .	. . .	. . .
5456	Sheet and plate	B 209	. . .	QQ-A-250/9	. . .	SB209	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	SB221	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	SB241	. . .
	Tube: drawn, seamless	B 210	. . .	. . .	. . .	. . .	. . .
	Armor plate	. . .	MIL-A-46027	. . .	. . .	. . .	. . .
	Extruded armor	. . .	MIL-A-46083	. . .	. . .	. . .	. . .
	Forged armor	. . .	MIL-A-45225	. . .	. . .	. . .	. . .
5457	Sheet	B 209	. . .	. . .	. . .	. . .	. . .
5554	Welding rod and electrodes: bare	. . .	. . .	. . .	. . .	. . .	A5.10
5556	Welding rod and electrodes: bare	. . .	. . .	. . .	. . .	. . .	A5.10
5652	Sheet and plate	B 209	. . .	. . .	. . .	SB209	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	. . .	. . .
5654	Welding rod and electrodes: bare	. . .	. . .	. . .	. . .	. . .	A5.10
5657	Sheet	B 209	. . .	. . .	. . .	. . .	. . .
6005	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
6053	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
6061	Sheet and plate	B 209	. . .	QQ-A-250/11	4025	SB209	. . .

		. . .	. . .	. . .	4026	. . .	. . .
		. . .	. . .	. . .	4027	. . .	. . .
	Tread plate	B 632	. . .	. . .	. . .	. . .	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	QQ-A-225/8	4115	SB211	. . .
		. . .	. . .	. . .	4116	. . .	. . .
		. . .	. . .	. . .	4117	. . .	. . .
		. . .	. . .	. . .	4128	. . .	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	4150	. . .	. . .
		. . .	. . .	. . .	4160	. . .	. . .
		. . .	. . .	. . .	4161	. . .	. . .
		. . .	. . .	. . .	4172	. . .	. . .
		. . .	. . .	. . .	4173	. . .	. . .
	Structural profiles (shapes)	B 308	. . .	. . .	4113	SB308	. . .
	Tube: drawn	B 483	. . .	. . .	. . .	. . .	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	SB 241	. . .
	Tube: drawn, seamless	B 210	. . .	WW-T-700/6	4079	SB210	. . .
		. . .	. . .	. . .	4080	. . .	. . .
		. . .	. . .	. . .	4082	. . .	. . .
	Tube: hydraulic	. . .	. . .	. . .	4081	. . .	. . .
		. . .	. . .	. . .	4083	. . .	. . .

	Tube: condenser	B 234	. . .	. . .	. . .	SB 234	. . .
	Tube: condenser with integral fins	B 404	. . .	. . .	. . .	. . .	. . .
	Tube: welded	B 313	. . .	. . .	. . .	. . .	. . .
		B 547	. . .	. . .	. . .	. . .	. . .
	Pipe	B 241	MIL-P-25995	. . .	. . .	SB 241	. . .
	Pipe: gas and oil transmission	B 345	. . .	. . .	. . .	. . .	. . .
	Forgings and forging stock	B 247	MIL-A-22771	. . .	4127	SB247	. . .
		. . .	. . .	. . .	4146	. . .	. . .
		. . .	. . .	. . .	4248	. . .	. . .
	Rings: forged or rolled	. . .	. . .	. . .	4312	. . .	. . .
	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
	Impacts	. . .	MIL-A-12545	. . .	. . .	. . .	. . .
	Structural pipe and tube: extruded	B 429	. . .	. . .	. . .	. . .	. . .
	Foil	. . .	. . .	. . .	4009	. . .	. . .
Alclad 6061	Sheet and plate	B 209	. . .	. . .	. . .	SB209	. . .
		. . .	. . .	. . .	4021	. . .	. . .
6063	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	4156	SB221	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	SB241	. . .
	Tube: extruded, coiled	B 491	. . .	. . .	. . .	. . .	. . .

	Tube: drawn	B 483	. . .	. . .	. . .	. . .	. . .
	Tube: drawn, seamless	B 210	. . .	. . .	. . .	SB210	. . .
	Pipe	B 241	MIL-P-25995	. . .	. . .	SB241	. . .
	Pipe: gas and oil transmission	B 345	. . .	. . .	. . .	. . .	. . .
	Structural pipe and tube: extruded	B 429	. . .	. . .	. . .	. . .	. . .
6066	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
	Forgings and forging stock	B 247	. . .	. . .	. . .	. . .	. . .
6070	Rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
	Impacts	. . .	MIL-A-12545	. . .	. . .	. . .	. . .
	Pipe: gas and oil transmission	B 345	. . .	. . .	. . .	. . .	. . .
6101	Bus conductor	B 317	. . .	QQ-B-825	. . .	. . .	. . .
6105	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
6151	Forgings and forging stock	B 247	MIL-A-22771	. . .	4125	. . .	. . .
6201	Wire: T81 temper	B 398	. . .	. . .	. . .	. . .	. . .
	Stranded conductor: T81 temper	B 399	. . .	. . .	. . .	. . .	. . .
6262	Wire, rod, and bar: rolled or cold finished	B 211	. . .	QQ-A-225/10	. . .	. . .	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
	Tube: drawn, seamless	B 210	. . .	. . .	. . .	. . .	. . .

	Tube: drawn	B 483	. . .	. . .	. . .	. . .	. . .
6351	Pipe: gas and oil transmission	B 345	. . .	. . .	. . .	. . .	. . .
	Seamless pipe and tube: extruded	B 241	. . .	. . .	. . .	. . .	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
6463	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
7005	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
7049	Forgings	B 247	MIL-A-22771	. . .	4111	. . .	. . .
	Extrusion	. . .	. . .	. . .	4157	. . .	. . .
	Extrusion	. . .	. . .	. . .	4159	. . .	. . .
	Hand forging	. . .	. . .	. . .	4247	. . .	. . .
	Forging	. . .	. . .	. . .	4321	. . .	. . .
	Plate	. . .	. . .	. . .	4200	. . .	. . .
7050	Plate	. . .	. . .	. . .	4050	. . .	. . .
		. . .	. . .	. . .	4201	. . .	. . .
	Wire, rod, and bar: extruded	. . .	. . .	. . .	4340	. . .	. . .
		. . .	. . .	. . .	4341	. . .	. . .
		. . .	. . .	. . .	4342	. . .	. . .
	Forgings	B 247	MIL-A-22771	. . .	4107	. . .	. . .
		. . .	. . .	. . .	4108	. . .	. . .

	Die forgings	. . .	. . .	. . .	4333	. . .	. . .
	Rivet wire and rod	B 316	. . .	QQ-A-430	. . .	. . .	. . .
Alclad 7050	Sheet	. . .	. . .	. . .	4243	. . .	. . .
7075	Sheet and plate	B 209	. . .	QQ-A-250/12	4024	. . .	. . .
		. . .	. . .	QQ-A-250/24	4044	. . .	. . .
		. . .	. . .	. . .	4045	. . .	. . .
		. . .	. . .	. . .	4078	. . .	. . .
	Wire, rod, and bar: rolled or cold finished	B 211	. . .	QQ-A-225/9	4122	. . .	. . .
		. . .	. . .	. . .	4123	. . .	. . .
		. . .	. . .	. . .	4124	. . .	. . .
		. . .	. . .	. . .	4186	. . .	. . .
		. . .	. . .	. . .	4187	. . .	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	4154	. . .	. . .
		. . .	. . .	. . .	4166	. . .	. . .
		. . .	. . .	. . .	4167	. . .	. . .
		. . .	. . .	. . .	4168	. . .	. . .
		. . .	. . .	. . .	4169	. . .	. . .
	Tube: extruded	B 241	. . .	. . .	. . .	. . .	. . .
	Tube: drawn, seamless	B 210	. . .	WW-T-700/7	. . .	. . .	. . .

	Forgings and forging stock	B 247	MIL-A-22771	. . .	. . .	. . .	. . .
		. . .	. . .	. . .	4141	. . .	. . .
		. . .	. . .	. . .	4126	. . .	. . .
		. . .	. . .	. . .	4131	. . .	. . .
		. . .	. . .	. . .	4147	. . .	. . .
	Hand forgings	. . .	. . .	. . .	4323	. . .	. . .
	Rings: forged or rolled	. . .	. . .	. . .	4311	. . .	. . .
		. . .	. . .	. . .	4310	. . .	. . .
	Impacts	. . .	MIL-A-12545	. . .	. . .	. . .	. . .
	Rivet wire	B 316	. . .	QQ-A-430	. . .	. . .	. . .
Alclad 7075	Sheet and plate	B 209	. . .	QQ-A-250/13	. . .	. . .	. . .
		. . .	. . .	QQ-A-250/25	4048	. . .	. . .
		. . .	. . .	QQ-A-250/26	4049	. . .	. . .
		. . .	. . .	. . .	4196	. . .	. . .
		. . .	. . .	. . .	4197	. . .	. . .
Alclad one side 7075	Sheet and plate	B 209	. . .	QQ-A-250/18	4046	. . .	. . .
Alclad 7475	Sheet	. . .	. . .	. . .	4100	. . .	. . .
		. . .	. . .	. . .	4207	. . .	. . .
7175	Extruded	. . .	. . .	. . .	4344	. . .	. . .

	Forgings and forging stock	B 247	MIL-A-22771	. . .	4148	. . .	. . .
		. . .	. . .	. . .	4149	. . .	. . .
		. . .	. . .	. . .	4179	. . .	. . .
7178	Sheet and plate	B 209	. . .	QQ-A-250/14	. . .	. . .	. . .
		. . .	. . .	QQ-A-250/21	. . .	. . .	. . .
	Wire, rod, bar, profiles (shapes), and tube: extruded	B 221	. . .	. . .	. . .	. . .	. . .
	Rivet wire	B 316	. . .	. . .	. . .	. . .	. . .
	Tube: extruded, seamless	B 241	. . .	. . .	. . .	. . .	. . .
Alclad 7178	Sheet and plate	B 209	. . .	QQ-A-250/15	4051	. . .	. . .
		. . .	. . .	QQ-A-250/22	. . .	. . .	. . .
		. . .	. . .	QQ-A-250/28	. . .	. . .	. . .
7475	Sheet and plate	. . .	. . .	. . .	4084	. . .	. . .
		. . .	. . .	. . .	4085	. . .	. . .
		. . .	. . .	. . .	4089	. . .	. . .
		. . .	. . .	. . .	4090	. . .	. . .
		. . .	. . .	. . .	4202	. . .	. . .

Properties of Wrought Aluminum Alloys

Table 1 Nominal densities and specific gravities of wrought aluminums and aluminum alloys

Density and specific gravity are dependent on composition, and variations are discernible from one cast to another for most alloys. The nominal values given here should not be specified as engineering requirements but are used in calculating typical values for weight per unit length, weight per unit area, covering area, etc. The density values were derived from metric and subsequently rounded; these values are not to be back-converted to the metric.

Alloy	Density, lb/in.^{3}	Specific gravity
1050	0.0975	2.705
1060	0.0975	2.705
1100	0.098	2.71
1145	0.0975	2.700
1175	0.0975	2.700
1200	0.098	2.70
1230	0.098	2.70
1235	0.0975	2.705
1345	0.0975	2.705
1350	0.0975	2.705
2011	0.102	2.83
2014	0.101	2.80
2017	0.101	2.79
2018	0.102	2.82
2024	0.101	2.78
2025	0.101	2.81
2036	0.100	2.75

2117	0.099	2.75
2124	0.100	2.78
2218	0.101	2.81
2219	0.103	2.84
2618	0.100	2.76
3003	0.099	2.73
3004	0.098	2.72
3005	0.098	2.73
3105	0.098	2.72
4032	0.097	2.68
4043	0.097	2.69
4045	0.096	2.67
4047	0.096	2.66
4145	0.099	2.74
4343	0.097	2.68
4643	0.097	2.69
5005	0.098	2.70
5050	0.097	2.69
5052	0.097	2.68
5056	0.095	2.64
5083	0.096	2.66

5086	0.096	2.66
5154	0.096	2.66
5183	0.096	2.66
5252	0.096	2.67
5254	0.096	2.66
5356	0.096	2.64
5454	0.097	2.69
5456	0.096	2.66
5457	0.097	2.69
5554	0.097	2.69
5556	0.096	2.66
5652	0.097	2.67
5654	0.096	2.66
5657	0.097	2.69
6003	0.097	2.70
6005	0.097	2.70
6053	0.097	2.69
6061	0.098	2.70
6063	0.097	2.70
6066	0.098	2.72
6070	0.098	2.71

6101	0.097	2.70
6105	0.097	2.69
6151	0.098	2.71
6162	0.097	2.70
6201	0.097	2.69
6262	0.098	2.72
6351	0.098	2.71
6463	0.097	2.69
6951	0.098	2.70
7005	0.100	2.78
7008	0.100	2.78
7049	0.103	2.84
7050	0.102	2.83
7072	0.098	2.72
7075	0.101	2.81
7178	0.102	2.83
8017	0.098	2.71
8030	0.098	2.71
8176	0.098	2.71
8177	0.098	2.70

Table 2 Typical physical properties of wrought aluminum alloys

Alloy	Average coefficient of thermal expansion(a)		Approximate melting range(b)(c)		Temper	Thermal conductivity at 25 °C (77 °F)		Electrical conductivity at 20 °C (68 °F), %IACS		Electrical resistivity at 20 °C (68 °F)	
	µm · °C	**µin./in. · °F**	**°C**	**°F**		**W/m · °C**	**Btu · in./ft^2 · h · °F**	**Equal volume**	**Equal weight**	**Ω· mm^2/m**	**Ω· circ mil/ft**
1060	23.6	13.1	645-655	1195-1215	O	234	1625	62	204	0.028	17
					H18	230	1600	61	201	0.028	17
1100	23.6	13.1	643-655	1190-1215	O	222	1540	59	194	0.030	18
					H18	218	1510	57	187	0.030	18
1350	23.75	13.2	645-655	1195-1215	All	234	1625	62	204	0.028	17
2011	22.9	12.7	540-643(d)	1005-1190(d)	T3	151	1050	39	123	0.045	27
					T8	172	1190	45	142	0.038	23
2014	23.0	12.8	507-638(e)	945-1180(e)	O	193	1340	50	159	0.035	21
					T4	134	930	34	108	0.0515	31
					T6	154	1070	40	127	0.043	26
2017	23.6	13.1	513-640(e)	955-1185(e)	OH	193	1340	50	159	0.035	21
					T4	134	930	34	108	0.0515	31
2018	22.3	12.4	507-638(d)	945-1180(d)	T61	154	1070	40	127	0.043	26
2024	23.2	12.9	500-638(e)	935-1180(e)	O	193	1340	50	160	0.035	21
					T3, T4, T361	121	840	30	96	0.058	35
					T6, T81, T861	151	1050	38	122	0.045	27

2025	22.7	12.6	520-640(e)	970-1185(e)	T6	154	1070	40	128	0.043	26
2036	23.4	13.0	555-650(d)	1030-1200(d)	T4	159	1100	41	135	0.0415	25
2117	23.75	13.2	555-650(d)	1030-1200(d)	T4	154	1070	40	130	0.043	26
2124	22.9	12.7	500-638(e)	935-1180(e)	T851	152	1055	38	122	0.045	27
2218	22.3	12.4	505-635(e)	940-1175(e)	T72	154	1070	40	126	0.043	26
2219	22.3	12.4	543-643(e)	1010-1190(e)	O	172	1190	44	138	0.040	24
					T31, T37	112	780	28	88	0.0615	37
					T6, T81, T87	121	840	30	94	0.058	35
2618	22.3	12.4	550-638	1020-1180	T6	147	1020	37	120	0.0465	28
3003	23.2	12.9	643-655	1190-1210	O	193	1340	50	163	0.035	21
					H12	163	1130	42	137	0.0415	25
					H14	159	1100	41	134	0.0415	25
					H18	154	1070	40	130	0.043	26
3004	23.9	13.3	630-655	1165-1210	All	163	1130	42	137	0.0415	25
3105	23.6	13.1	635-655	1175-1210	All	172	1190	45	148	0.038	23
4032	19.4	10.8	532-570(e)	990-1060(e)	O	154	1070	40	132	0.043	26
					T6	138	960	35	116	0.050	30
4043	22.1	12.3	575-632	1065-1170	O	163	1130	42	140	0.0415	25

4045	21.05	11.7	575-600	1065-1110	All	172	1190	45	151	0.038	23
4343	21.6	12.0	577-613	1070-1135	All	180	1250	42	158	0.0415	25
5005	23.75	13.2	632-655	1170-1210	All	200	1390	52	172	0.033	20
5050	23.75	13.2	625-650	1155-1205	All	193	1340	50	165	0.035	21
5052	23.75	13.2	607-650	1125-1200	All	138	960	35	116	0.050	30
5056	24.1	13.4	568-638	1055-1180	O	117	810	29	98	0.060	36
					H38	108	750	27	91	0.063	38
5083	23.75	13.2	590-638	1095-1180	O	117	810	29	98	0.060	36
5086	23.75	13.2	585-640	1085-1185	All	125	870	31	104	0.055	33
5154	23.9	13.3	593-643	1100-1190	All	125	870	32	107	0.053	32
5252	23.75	13.2	607-650	1125-1200	All	138	960	35	116	0.050	30
5254	23.9	13.3	593-643	1100-1190	All	125	870	32	107	0.053	32
5356	24.1	13.4	570-635	1060-1175	O	117	810	29	98	0.060	36
5454	23.6	13.1	600-645	1115-1195	O	134	930	34	113	0.0515	31
					H38	134	930	34	113	0.0515	31
5456	23.9	13.3	568-638	1055-1180	O	117	810	29	98	0.060	36
5457	23.75	13.2	630-655	1165-1210	All	176	1220	46	153	0.038	23

5652	23.75	13.2	607-650	1125-1200	All	138	960	35	116	0.050	30
5657	23.75	13.2	638-657	1180-1215	All	205	1420	54	180	0.0315	19
6005	23.4	13.0	610-655(d)	1125-1210(d)	T1	180	1250	47	155	0.0365	22
					T5	190	1310	49	161	0.035	21
6053	23	12.8	575-650(d)	1070-1205(d)	O	172	1190	45	148	0.038	23
					T4	154	1070	40	132	0.043	26
					T6	163	1130	42	139	0.0415	25
6061	23.6	13.1	580-650(d)	1080-1205(d)	O	180	1250	47	155	0.0365	22
					T4	154	1070	40	132	0.043	26
					T6	167	1160	43	142	0.040	24
6063	23.4	13.0	615-655	1140-1210	O	218	1510	58	191	0.030	18
					T1	193	1340	50	165	0.035	21
					T5	209	1450	55	181	0.032	19
					T6, T83	200	1390	53	175	0.033	20
6066	23.2	12.9	565-645(e)	1045-1195(e)	O	154	1070	40	132	0.043	26
					T6	147	1020	37	122	0.0465	28
6070	. . .	. . .	565-650(e)	1050-1200(e)	T6	172	1190	44	145	0.040	24
6101	23.4	13.0	620-655	1150-1210	T6	218	1510	57	188	0.030	18
					T61	222	1540	59	194	0.030	18
					T63	218	1510	58	191	0.030	18

					T64	226	1570	60	198	0.028	17
					T65	218	1510	58	191	0.030	18
6105	23.4	13.0	600-650(d)	1110-1200(d)	T1	176	1220	46	151	0.038	23
					T5	193	1340	50	165	0.035	21
6151	23.2	12.9	590-650(d)	1090-1200(d)	O	205	1420	54	178	0.0315	19
					T4	163	1130	42	138	0.0415	25
					T6	172	1190	45	148	0.038	23
6201	23.4	13.0	607-655(d)	1125-1210(d)	T81	205	1420	54	180	0.0315	19
6253	. . .	. . .	600-650	1100-1205	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6262	23.4	13.0	580-650(d)	1080-1205(d)	T9	172	1190	44	145	0.040	24
6351	23.4	13.0	555-650	1030-1200	T6	176	1220	46	151	0.038	23
6463	23.4	13.0	615-655	1140-1210	T1	193	1340	50	165	0.035	21
					T5	209	1450	55	181	0.0315	19
					T6	200	1390	53	175	0.033	20
6951	23.4	13.0	615-655	1140-1210	O	213	1480	56	186	0.0315	19
					T6	198	1370	52	172	0.033	20
7049	23.4	13.0	475-635	890-1175	T73	154	1070	40	132	0.043	26
7050	24.1	13.4	490-630	910-1165	T74(f)	157	1090	41	135	0.0415	25
7072	23.6	13.1	640-	1185-	O	222	1540	59	193	0.030	18

			655	1215							
7075	23.6	13.1	475-635(g)	890-1175(g)	T6	130	900	3	105	0.0515	31
7175	23.4	13.0	475-635(g)	890-1175(g)	T74	156	1080	39	124	0.043	26
7178	23.4	13.0	475-630(g)	890-1165(g)	T6	125	870	31	98	0.055	33
7475	23.2	12.9	475-635(g)	890-1175(g)	T61, T651	138	960	35	116	0.050	30
					T76, T761	147	1020	40	132	0.043	26
					T7351	163	1130	42	139	0.0415	25
8017	23.6	13.1	645-655	1190-1215	H12, H22	. . .	. . .	59	193	0.030	18
					H212	. . .	. . .	61	200	0.028	17
8030	23.6	13.1	645-655	1190-1215	H221	230	1600	61	201	0.028	17
8176	23.6	13.1	645-655	1190-1215	H24	230	1600	61	201	0.028	17

(a) Coefficient from 20 to 100 °C (68 to 212 °F).

(b) Melting ranges shown apply to wrought products of 6.35 mm ($\frac{1}{4}$ in.) thickness or greater.

(c) Based on typical composition of the indicated alloys.

(d) Eutectic melting can be completely eliminated by homogenization.

(e) Eutectic melting is not eliminated by homogenization.

(f) Although not formerly registered, the literature and some specifications have used T736 as the designation for this temper.

(g) Homogenization can raise eutectic melting temperature 10 to 20 °C (20 to 40 °F) but usually does not eliminate eutectic melting.

Table 3 Typical mechanical properties of wrought aluminum and aluminum alloys

The following typical properties are not guaranteed, because in most cases they are averages for various sizes, product forms, and methods of manufacture and may not be exactly representative of any one particular product or size. The data are intended only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes.

Alloy and temper	Ultimate tensile strength		Tensile yield strength		Elongation in 50 mm (2 in.), %		Hardness, HB(a)	Ultimate Shearing strength		Fatigue endurance limit(b)		Modulus of elasticity(c)	
	MPa	**ksi**	**MPa**	**ksi**	**1.6 mm ($\frac{1}{16}$ in.) thick specimen**	**1.3 mm ($\frac{1}{2}$ in.) diam specimen**		**MPa**	**ksi**	**MPa**	**ksi**	**GPa**	**10^6 psi**
1060-O	70	10	30	4	43	. . .	19	50	7	20	3	69	10.0
1060-H12	85	12	75	11	16	. . .	23	55	8	30	4	69	10.0
1060-H14	95	14	90	13	12	. . .	26	60	9	35	5	69	10.0
1060-H16	110	16	105	15	8	. . .	30	70	10	45	6.5	69	10.0
1060-H18	130	19	125	18	6	. . .	35	75	11	45	6.5	69	10.0
1100-O	90	13	35	5	35	45	23	60	9	35	5	69	10.0
1100-H12	110	16	105	15	12	25	28	70	10	40	6	69	10.0
1100-H14	125	18	115	17	9	20	32	75	11	50	7	69	10.0
1100-H16	145	21	140	20	6	17	38	85	12	60	9	69	10.0
1100-H18	165	24	150	22	5	15	44	90	13	60	9	69	10.0
1350-O	85	12	30	4	. . .	(d)	. . .	55	8	. . .	. . .	69	10.0
1350-H12	95	14	85	12	. . .	. . .	. . .	60	9	. . .	. . .	69	10.0
1350-H14	110	16	95	14	. . .	. . .	. . .	70	10	. . .	. . .	69	10.0
1350-H16	125	18	110	16	. . .	. . .	. . .	75	11	. . .	. . .	69	10.0
1350-H19	185	27	165	24	. . .	(e)	. . .	105	15	50	7	69	10.0
2011-T3	380	55	295	43	. . .	15	95	220	32	125	18	70	10.2

2011-T8	405	59	310	45	. . .	12	100	240	35	125	18	70	10.2
2014-O	185	27	95	14	. . .	18	45	125	18	90	13	73	10.6
2014-T4, T451	425	62	290	42	. . .	20	105	260	38	140	20	73	10.6
2014-T6, T651	485	70	415	60	. . .	13	135	290	42	125	18	73	10.6
Alclad 2014-O	175	25	70	10	21	. . .	. . .	125	18	. . .	. . .	72	10.5
Alclad 2014-T3	435	63	275	40	20	. . .	. . .	255	37	. . .	. . .	72	10.5
Alclad 2014-T4, T451	420	61	255	37	22	. . .	. . .	255	37	. . .	. . .	72	10.5
Alclad 2014-T6, T651	470	68	415	60	10	. . .	. . .	285	41	. . .	. . .	72	10.5
2017-O	180	26	70	10	. . .	22	45	125	18	90	13	72	10.5
2017-T4, T451	425	61	255	37	22	. . .	. . .	255	37	. . .	. . .	72	10.5
2018-T61	420	61	315	46	. . .	12	120	270	39	115	17	74	10.8
2024-O	185	27	75	11	20	22	47	125	18	90	13	73	10.6
2024-T3	485	70	345	50	18	. . .	120	285	41	140	20	73	10.6
2024-T4, T351	470	68	325	47	20	19	120	285	41	140	20	73	10.6
2024-T361(f)	495	72	395	57	13	. . .	130	290	42	125	18	73	10.6
Alclad 2024-O	180	26	75	11	20	. . .	. . .	125	18	. . .	. . .	73	10.6
Alclad 2024-T3	450	65	310	45	18	. . .	. . .	275	40	. . .	. . .	73	10.6
Alclad 2024-	440	64	290	42	19	. . .	. . .	275	40	. . .	. . .	73	10.6

T4, T351													
Alclad 2024-T361(f)	460	67	365	53	11	. . .	. . .	285	41	. . .	. . .	73	10.6
Alclad 2024-T81, T851	450	65	415	60	6	. . .	. . .	275	40	. . .	. . .	73	10.6
Alclad 2024-T861(f)	485	70	455	66	6	. . .	. . .	290	42	. . .	. . .	73	10.6
2025-T6	400	58	255	37	. . .	19	110	240	35	125	18	71	10.4
2036-T4	340	49	195	28	24	. . .	. . .	. . .	. . .	125(g)	18(g)	71	10.3
2117-T4	295	43	165	24	. . .	27	70	195	28	95	14	71	10.3
2124-T851	485	70	440	64	. . .	8	. . .	. . .	. . .	. . .	. . .	73	10.6
2218-T72	330	48	255	37	. . .	11	95	205	30	. . .	. . .	74	10.8
2219-O	175	25	75	11	18	. . .	. . .	. . .	. . .	. . .	. . .	73	10.6
2219-T42	360	52	185	27	20	. . .	. . .	. . .	. . .	. . .	. . .	73	10.6
2219-T31, T351	360	52	250	36	17	. . .	. . .	. . .	. . .	. . .	. . .	73	10.6
2219-T37	395	57	315	46	11	. . .	. . .	. . .	. . .	. . .	. . .	73	10.6
2219-T62	415	60	290	42	10	. . .	. . .	. . .	. . .	105	15	73	10.6
2219-T81, T851	455	66	350	51	10	. . .	. . .	. . .	. . .	105	15	73	10.6
2219-T87	475	69	395	57	10	. . .	. . .	. . .	. . .	105	15	73	10.6
2618-T61	440	64	370	54	. . .	10	115	260	38	125	18	74	10.8
3003-O	110	16	40	6	30	40	28	75	11	50	7	69	10.0
3003-H12	130	19	125	18	10	20	35	85	12	55	8	69	10.0

3003-H14	150	22	145	21	8	16	40	95	14	60	9	69	10.0
3003-H16	180	26	170	25	5	14	47	105	15	70	10	69	10.0
3003-H18	200	29	185	27	4	10	55	110	16	70	10	69	10.0
Alclad 3003-O	110	16	40	6	30	40	. . .	75	11	. . .	. . .	. . .	. . .
Alclad 3003-H12	130	19	125	18	10	20	. . .	85	12	. . .	. . .	69	10.0
Alclad 3003-H14	150	22	145	21	8	16	. . .	95	14	. . .	. . .	69	10.0
Alclad 3003-H16	180	26	170	25	5	14	. . .	105	15	. . .	. . .	69	10.0
Alclad 3003-H18	200	29	185	27	4	10	. . .	110	16	. . .	. . .	69	10.0
3004-O	180	26	70	10	20	25	45	110	16	95	14	69	10.0
3004-H32	215	31	170	25	10	17	52	115	17	105	15	69	10.0
3004-H34	240	35	200	29	9	12	63	125	18	105	15	69	10.0
3004-H36	260	38	230	33	5	9	70	140	20	110	16	69	10.0
3004-H38	285	41	250	36	5	6	77	145	21	110	16	69	10.0
Alclad 3004-O	180	26	70	10	20	25	. . .	110	16	. . .	. . .	69	10.0
Alclad 3004-H32	215	31	170	25	10	17	. . .	115	17	. . .	. . .	69	10.0
Alclad 3004-H34	240	35	200	29	9	12	. . .	125	18	. . .	. . .	69	10.0
Alclad 3004-H36	260	38	230	33	5	9	. . .	140	20	. . .	. . .	69	10.0
Alclad 3004-H38	285	41	250	36	5	6	. . .	145	21	. . .	. . .	69	10.0

3105-O	115	17	55	8	24	. . .	. . .	85	12	. . .	. . .	69	10.0
3105-H12	150	22	130	19	7	. . .	. . .	95	14	. . .	. . .	69	10.0
3105-H14	170	25	150	22	5	. . .	. . .	105	15	. . .	. . .	69	10.0
3105-H16	195	28	170	25	4	. . .	. . .	110	16	. . .	. . .	69	10.0
3105-H18	215	31	195	28	3	. . .	. . .	115	17	. . .	. . .	69	10.0
3105-H25	180	26	160	23	8	. . .	. . .	105	15	. . .	. . .	69	10.0
4032-T6	380	55	315	46	. . .	9	120	260	38	110	16	79	11.4
5005-O	125	18	40	6	25	. . .	28	75	11	. . .	. . .	69	10.0
5005-H12	140	20	130	19	10	. . .	. . .	95	14	. . .	. . .	69	10.0
5005-H14	160	23	150	22	6	. . .	. . .	95	14	. . .	. . .	69	10.0
5005-H16	180	26	170	25	5	. . .	. . .	105	15	. . .	. . .	69	10.0
5005-H18	200	29	195	28	4	. . .	. . .	110	16	. . .	. . .	69	10.0
5005-H32	140	20	115	17	11	. . .	36	95	14	. . .	. . .	69	10.0
5005-H34	160	23	140	20	8	. . .	41	95	14	. . .	. . .	69	10.0
5005-H36	180	26	165	24	6	. . .	46	105	15	. . .	. . .	69	10.0
5005-H38	200	29	185	27	5	. . .	51	110	16	. . .	. . .	69	10.0
5050-O	145	21	55	8	24	. . .	36	105	15	85	12	69	10.0
5050-H32	170	25	145	21	9	. . .	46	115	17	90	13	69	10.0
5050-H34	195	28	165	24	8	. . .	53	125	18	90	13	69	10.0
5050-H36	205	30	180	26	7	. . .	58	130	19	95	14	69	10.0
5050-H38	220	32	200	29	6	. . .	63	140	20	95	14	69	10.0

5052-O	195	28	90	13	25	30	47	125	18	110	16	70	10.2
5052-H32	230	33	195	28	12	18	60	140	20	115	17	70	10.2
5052-H34	260	38	215	31	10	14	68	145	21	125	18	70	10.2
5052-H36	275	40	240	35	8	10	73	160	23	130	19	70	10.2
5052-H38	290	42	255	37	7	8	77	165	24	140	20	70	10.2
5056-O	290	42	150	22	. . .	35	65	180	26	140	20	71	10.3
5056-H18	435	63	405	59	. . .	10	105	235	34	150	22	71	10.3
5056-H38	415	60	345	50	. . .	15	100	220	32	150	22	71	10.3
5083-O	290	42	145	21	. . .	22	. . .	170	25	. . .	. . .	71	10.3
5083-H321, H116	315	46	230	33	. . .	16	. . .	. . .	. . .	160	23	71	10.3
5086-O	260	38	115	17	22	. . .	. . .	160	23	. . .	. . .	71	10.3
5086-H32, H116	290	42	205	30	12	. . .	. . .	. . .	. . .	. . .	. . .	71	10.3
5086-H34	325	47	255	37	10	. . .	. . .	185	27	. . .	. . .	71	10.3
5086-H112	270	39	130	19	14	. . .	. . .	. . .	. . .	. . .	. . .	71	10.3
5154-O	240	35	115	17	27	. . .	58	150	22	115	17	70	10.2
5154-H32	270	39	205	30	15	. . .	67	150	22	125	18	70	10.2
5154-H34	290	42	230	33	13	. . .	73	165	24	130	19	70	10.2
5154-H36	310	45	250	36	12	. . .	78	180	26	140	20	70	10.2
5154-H38	330	48	270	39	10	. . .	80	195	28	145	21	70	10.2
5154-H112	240	35	115	17	25	. . .	63	. . .	. . .	115	17	70	10.2

5252-H25	235	34	170	25	11	. . .	68	145	21	. . .	. . .	69	10.0
5252-H38, H28	285	41	240	35	5	. . .	75	160	23	. . .	. . .	69	10.0
5254-O	240	35	115	17	27	. . .	58	150	22	115	17	70	10.2
5254-H32	270	39	205	30	15	. . .	67	150	22	125	18	70	10.2
5254-H34	290	42	230	33	13	. . .	73	165	24	130	19	70	10.2
5254-H36	310	45	250	36	12	. . .	78	180	26	140	20	70	10.2
5254-H38	330	48	270	39	10	. . .	80	195	28	145	21	70	10.2
5254-H112	240	35	115	17	25	. . .	63	. . .	. . .	115	17	70	10.2
5454-O	250	36	115	17	22	. . .	62	160	23	. . .	. . .	70	10.2
5454-H32	275	40	205	30	10	. . .	73	165	24	. . .	. . .	70	10.2
5454-H34	305	44	240	35	10	. . .	81	180	26	. . .	. . .	70	10.2
5454-H111	260	38	180	26	14	. . .	70	160	23	. . .	. . .	70	10.2
5454-H112	250	36	125	18	18	. . .	62	160	23	. . .	. . .	70	10.2
5456-O	310	45	160	23	. . .	24	. . .	. . .	. . .	. . .	. . .	71	10.3
5456-H112	310	45	165	24	. . .	22	. . .	. . .	. . .	. . .	. . .	71	10.3
5456-H321, H116	350	51	255	37	. . .	16	90	205	30	. . .	. . .	71	10.3
5457-O	130	19	50	7	22	. . .	32	85	12	. . .	. . .	69	10.0
5457-H25	180	26	160	23	12	. . .	48	110	16	. . .	. . .	69	10.0
5457-H38, H28	205	30	185	27	6	. . .	55	125	18	. . .	. . .	69	10.0
5652-O	195	28	90	13	25	30	47	125	18	110	16	70	10.2

5652-H32	230	33	195	28	12	18	60	140	20	115	17	70	10.2
5652-H34	260	38	215	31	10	14	68	145	21	125	18	70	10.2
5652-H36	275	40	240	35	8	10	73	160	23	130	19	70	10.2
5652-H38	290	42	255	37	7	8	77	165	24	140	20	70	10.2
5657-H25	160	23	140	20	12	. . .	40	95	14	. . .	. . .	69	10.0
5657-H38, H28	195	28	165	24	7	. . .	50	105	15	. . .	. . .	69	10.0
6061-O	125	18	55	8	25	30	30	85	12	60	9	69	10.0
6061-T4, T451	240	35	145	21	22	25	65	165	24	95	14	69	10.0
6061-T6, T651	310	45	275	40	12	17	95	205	30	95	14	69	10.0
Alclad 6061-O	115	17	50	7	25	. . .	. . .	75	11	. . .	. . .	69	10.0
Alclad 6061-T4, T451	230	33	130	19	22	. . .	. . .	150	22	. . .	. . .	69	10.0
Alclad 6061-T6, T651	290	42	255	37	12	. . .	. . .	185	27	. . .	. . .	69	10.0
6063-O	90	13	50	7	. . .	. . .	25	70	10	55	8	69	10.0
6063-T1	150	22	90	13	20	. . .	42	95	14	60	9	69	10.0
6063-T4	170	25	90	13	22	. . .	. . .	. . .	. . .	. . .	. . .	69	10.0
6063-T5	185	27	145	21	12	. . .	60	115	17	70	10	69	10.0
6063-T6	240	35	215	31	12	. . .	73	150	22	70	10	69	10.0
6063-T83	255	37	240	35	9	. . .	82	150	22	. . .	. . .	69	10.0
6063-T831	205	30	185	27	10	. . .	70	125	18	. . .	. . .	69	10.0

6063-T832	290	42	270	39	12	. . .	95	185	27	. . .	. . .	69	10.0
6066-O	150	22	85	12	. . .	18	43	95	14	. . .	. . .	69	10.0
6066-T4, T451	360	52	205	30	. . .	18	90	200	29	. . .	. . .	69	10.0
6066-T6, T651	395	57	360	52	. . .	12	120	235	34	110	16	69	10.0
6070-T6	380	55	350	51	10	. . .	. . .	235	34	95	14	69	10.0
6101-H111	95	14	75	11	. . .	. . .	. . .	. . .	. . .	. . .	. . .	69	10.0
6101-T6	220	32	195	28	15	. . .	71	140	20	. . .	. . .	69	10.0
6262-T9	400	58	380	55	. . .	10	120	240	35	90	13	69	10.0
6351-T4	250	36	150	22	20	. . .	. . .	. . .	. . .	. . .	. . .	69	10.0
6351-T6	310	45	285	41	14	. . .	95	200	29	90	13	69	10.0
6463-T1	150	22	90	13	20	. . .	42	95	14	70	10	69	10.0
6463-T5	185	27	145	21	12	. . .	60	115	17	70	10	69	10.0
6463-T6	240	35	215	31	12	. . .	74	150	22	70	10	69	10.0
7049-T73	515	75	450	65	. . .	12	135	305	44	. . .	. . .	72	10.4
7049-T7352	515	75	435	63	. . .	11	135	295	43	. . .	. . .	72	10.4
7050-T73510, T73511	495	72	435	63	. . .	12	. . .	. . .	. . .	. . .	. . .	72	10.4
7050-T7451[h]	525	76	470	68	. . .	11	. . .	305	44	. . .	. . .	72	10.4
7050-T7651	550	80	490	71	. . .	11	. . .	325	47	. . .	. . .	72	10.4
7075-O	230	33	105	15	17	16	60	150	22	. . .	. . .	72	10.4
7075-T6,	570	83	505	73	11	11	150	330	48	160	23	72	10.4

T651													
Alclad 7075-O	220	32	95	14	17	. . .	. . .	150	22	. . .	. . .	72	10.4
Alclad 7075-T6, T651	525	76	460	67	11	. . .	. . .	315	46	. . .	. . .	72	10.4
7175-T74	525	76	455	66	. . .	11	135	290	42	160	23	72	10.4
7178-O	230	33	105	15	15	16	. . .	. . .	. . .	. . .	. . .	72	10.4
7178-T6, T651	605	88	540	78	10	11	. . .	. . .	. . .	. . .	. . .	72	10.4
7178-T76, T7651	570	83	505	73	. . .	11	. . .	. . .	. . .	. . .	. . .	71	10.3
Alclad 7178-O	220	32	95	14	16	. . .	. . .	. . .	. . .	. . .	. . .	72	10.4
Alclad 7178-T6, T651	560	81	490	71	10	. . .	. . .	. . .	. . .	. . .	. . .	72	10.4
7475-T61	565	82	490	71	11	. . .	. . .	. . .	. . .	. . .	. . .	70	10.2
7475-T651	585	85	510	74	. . .	13	. . .	. . .	. . .	. . .	. . .	72	10.4
7475-T7351	495	72	420	61	. . .	13	. . .	. . .	. . .	. . .	. . .	72	10.4
7475-T761	515	75	450	65	12	. . .	. . .	. . .	. . .	. . .	. . .	70	10.2
7475-T7651	530	77	460	67	. . .	12	. . .	. . .	. . .	. . .	. . .	72	10.4
Alclad 7475-T61	515	75	455	66	11	. . .	. . .	. . .	. . .	. . .	. . .	70	10.2
Alclad 7475-T761	490	71	420	61	12	. . .	. . .	. . .	. . .	. . .	. . .	70	10.2
8176-H24	115	17	95	14	15	. . .	. . .	70	10	. . .	. . .	69	10.0

(a) 500 kg load and 10 mm ball.

(b) Based on 500,000,000 cycles of completely reversed stress using the R.R. Moore type machine and specimen.

(c) Average of tension and compression moduli. Compression modulus is ∼2% greater than tension modulus.

(d) 1350-0 wire will have an elongation of ∼23% in 250 mm (10 in.).

(e) 1350-H19 wire will have an elongation of approximately 1 $\frac{1}{2}$ % in 250 mm (10 in.).

(f) Tempers T361 and T861 were formerly designated T36 and T86, respectively.

(g) Based on 10^7 cycles using flexural type testing of sheet specimens.

(h) T7451, although not previously registered, has appeared in literature and in some specifications as T73651.

Table 4 Effect of temperature on the tensile strengths of wrought aluminum and aluminum alloys

Alloy and temper	Ultimate tensile strength(a), MPa (ksi), at:									
	-195 °C (-320 °F)	**-80 °C (-112 °F)**	**-30 °C (-18 °F)**	**24 °C (75 °F)**	**100 °C (212 °F)**	**150 °C (300 °F)**	**205 °C (400 °F)**	**260 °C (500 °F)**	**315 °C (600 °F)**	**370 °C (700 °F)**
1100-O	172 (25)	103 (15)	97 (14)	90 (13)	70 (10)	55 (8)	40 (6)	28 (4)	20 (2.9)	14 (2.1)
1100-H14	207 (30)	138 (20)	130 (19)	125 (18)	110 (16)	97 (14)	70 (10)	28 (4)	20 (2.9)	14 (2.1)
1100-H18	235 (34)	180 (26)	172 (25)	165 (24)	145 (21)	125 (18)	40 (6)	28 (4)	20 (2.9)	14 (2.1)
2011-T3	. . .	. . .	. . .	380 (55)	325 (47)	193 (28)	110 (16)	45 (6.5)	21 (3.1)	16 (2.3)
2014-T6, T651	580 (84)	510 (74)	495 (72)	483 (70)	435 (63)	275 (40)	110 (16)	66 (9.5)	45 (6.5)	30 (4.3)
2017-T4, T451	550 (80)	448 (65)	440 (64)	427 (62)	393 (57)	275 (40)	110 (16)	62 (9)	40 (6)	30 (4.3)
2024-T3 (sheet)	585 (85)	503 (73)	495 (72)	483 (70)	455 (66)	380 (55)	185 (27)	75 (11)	52 (7.5)	35 (5)
2024-T4, T351 (plate)	580 (84)	490 (71)	475 (69)	470 (68)	435 (63)	310 (45)	180 (26)	75 (11)	52 (7.5)	35 (5)

2024-T6, T651	580 (84)	495 (72)	483 (70)	475 (69)	448 (65)	310 (45)	180 (26)	75 (11)	52 (7.5)	35 (5)
2024-T81, T851	585 (85)	510 (74)	503 (73)	483 (70)	455 (66)	380 (55)	185 (27)	75 (11)	52 (7.5)	35 (5)
2024-T861	635 (92)	558 (81)	538 (78)	517 (75)	483 (70)	372 (54)	145 (21)	75 (11)	52 (7.5)	35 (5)
2117-T4	385 (56)	310 (45)	303 (44)	295 (43)	248 (36)	207 (30,)	110 (16)	52 (7.5)	32 (4.7)	20 (2.9)
2124-T851	593 (86)	525 (76)	503 (73)	483 (70)	455 (66)	372 (54)	185 (27)	75 (11)	52 (7.5)	38 (5.5)
2218-T61	495 (72)	420 (61)	407 (59)	407 (59)	385 (56)	283 (41)	152 (22)	70 (10)	38 (5.5)	28 (4)
2219-T62	503 (73)	435 (63)	415 (60)	400 (58)	372 (54)	310 (45)	235 (34)	185 (27)	70 (10)	30 (4.4)
2219-T81, T851	572 (83)	490 (71)	475 (69)	455 (66)	415 (60)	338 (49)	248 (36)	200 (29)	48 (7)	30 (4.4)
2618-T61	538 (78)	462 (67)	440 (64)	440 (64)	427 (62)	345 (50)	220 (32)	90 (13)	52 (7.5)	35 (5)
3003-O	228 (33)	138 (20)	117 (17)	110 (16)	90 (13)	75 (11)	59 (8.5)	40 (6)	28 (4)	19 (2.8)
3003-H14	240 (35)	165 (24)	152 (22)	152 (22)	145 (21)	125 (18)	97 (14)	52 (7.5)	28 (4)	19 (2.8)
3003-H18	283 (41)	220 (32)	207 (30)	200 (29)	180 (26)	160 (23)	97 (14)	52 (7.5)	28 (4)	19 (2.8)
3004-O	290 (42)	193 (28)	180 (26)	180 (26)	180 (26)	152 (22)	97 (14)	70 (10)	52 (7.5)	35 (5)
3004-H34	360 (52)	262 (38)	248 (36)	240 (35)	235 (34)	193 (28)	145 (21)	97 (14)	52 (7.5)	35 (5)
3004-H38	400 (58)	303 (44)	290 (42)	283 (41)	275 (40)	215 (31)	152 (22)	83 (12)	52 (7.5)	35 (5)
4032-T6	455 (66)	400 (58)	385 (56)	380 (55)	345 (50)	255 (37)	90 (13)	55 (8)	35 (5)	23 (3.4)

5050-O	255 (37)	152 (22)	145 (21)	145 (21)	145 (21)	130 (19)	97 (14)	62 (9)	40 (6)	27 (3.9)
5050-H34	303 (44)	207 (30)	193 (28)	193 (28)	193 (28)	172 (25)	97 (14)	62 (9)	40 (6)	27 (3.9)
5050-H38	317 (46)	235 (34)	220 (32)	220 (32)	215 (31)	185 (27)	97 (14)	62 (9)	40 (6)	27 (3.9)
5052-O	303 (44)	200 (29)	193 (28)	193 (28)	193 (28)	160 (23)	117 (17)	83 (12)	52 (7.5)	35 (5)
5052-H34	380 (55)	275 (40)	262 (38)	262 (38)	262 (38)	207 (30)	165 (24)	83 (12)	52 (7.5)	35 (5)
5052-H38	415 (60)	303 (44)	290 (42)	290 (42)	275 (40)	235 (34)	172 (25)	83 (12)	52 (7.5)	35 (5)
5083-O	407 (59)	295 (43)	290 (42)	290 (42)	275 (40)	215 (31)	152 (22)	117 (17)	75 (11)	40 (6)
5086-O	380 (55)	270 (39)	262 (38)	262 (38)	262 (38)	200 (29)	152 (22)	117 (17)	75 (11)	40 (6)
5154-O	360 (52)	248 (36)	240 (35)	240 (35)	240 (35)	200 (29)	152 (22)	117 (17)	75 (11)	40 (6)
5254-O	360 (52)	248 (36)	240 (35)	240 (35)	240 (35)	200 (29)	152 (22)	117 (17)	75 (11)	40 (6)
5454-O	372 (54)	255 (37)	248 (36)	248 (36)	248 (36)	200 (29)	152 (22)	117 (17)	75 (11)	40 (6)
5454-H32	407 (59)	290 (42)	283 (41)	275 (40)	270 (39)	220 (32)	172 (25)	117 (17)	75 (11)	40 (6)
5454-H34	435 (63)	317 (46)	303 (44)	303 (44)	295 (43)	235 (34)	180 (26)	117 (17)	75 (11)	40 (6)
5456-O	427 (62)	317 (46)	310 (45)	310 (45)	290 (42)	215 (31)	152 (22)	117 (17)	75 (11)	40 (6)
5652-O	303 (44)	200 (29)	193 (28)	193 (28)	193 (28)	160 (23)	117 (17)	83 (12)	52 (7.5)	35 (5)
5652-H34	380 (55)	275 (40)	262 (38)	262 (38)	262 (38)	207 (30)	165 (24)	83 (12)	52 (7.5)	35 (5)

5456-O	427 (62)	317 (46)	310 (45)	310 (45)	290 (42)	215 (31)	152 (22)	117 (17)	75 (11)	40 (6)
5652-O	303 (44)	200 (29)	193 (28)	193 (28)	193 (28)	160 (23)	117 (17)	83 (12)	52 (7.5)	35 (5)
5652-H34	380 (55)	275 (40)	262 (38)	262 (38)	262 (38)	207 (30)	165 (24)	83 (12)	52 (7.5)	35 (5)
5652-H38	415 (60)	303 (44)	290 (42)	290 (42)	275 (40)	235 (34)	172 (25)	83 (12)	52 (7.5)	35 (5)
6053-T6, T651	. . .	. . .	. . .	255 (37)	220 (32)	172 (25)	90 (13)	38 (5.5)	28 (4)	20 (2.9)
6061-T6, T651	415 (60)	338 (49)	325 (47)	310 (45)	290 (42)	235 (34)	130 (19)	52 (7.5)	32 (4.6)	21 (3)
6063-T1	235 (34)	180 (26)	165 (24)	152 (22)	152 (22)	145 (21)	62 (9)	31 (4.5)	22 (3.2)	16 (2.3)
6063-T5	255 (37)	200 (29)	193 (28)	185 (27)	165 (24)	138 (20)	62 (9)	31 (4.5)	22 (3.2)	16 (2.3)
6063-T6	325 (47)	262 (38)	248 (36)	240 (35)	215 (31)	145 (21)	62 (9)	31 (4.5)	22 (3.2)	16 (2.3)
6101-T6	295 (43)	248 (36)	235 (34)	220 (32)	193 (28)	145 (21)	70 (10)	33 (4.8)	21 (3)	17 (2.5)
6151-T6	393 (57)	345 (50)	338 (49)	330 (48)	295 (43)	193 (28)	97 (14)	45 (6.5)	33 (5)	28 (4)
6262-T651	415 (60)	338 (49)	325 (47)	310 (45)	290 (42)	235 (34)	. . .	. . .	. . .	. . .
6262-T9	510 (74)	427 (62)	415 (60)	400 (58)	365 (53)	262 (38)	103 (15)	59 (8.5)	32 (4.6)	21 (3)
7075-T6, T651	703 (102)	620 (90)	593 (86)	572 (83)	483 (70)	215 (31)	110 (16)	75 (11)	55 (8)	40 (6)
7075-T73, T7351	635 (92)	545 (79)	525 (76)	503 (73)	435 (63)	215 (31)	110 (16)	75 (11)	55 (8)	40 (6)
7178-T6, T651	730 (106)	648 (94)	627 (91)	607 (88)	503 (73)	215 (31)	103 (15)	75 (11)	59 (8.5)	45 (6.5)

7178-T76, T7651	730 (106)	627 (91)	607 (88)	572 (83)	475 (69)	215 (31)	103 (15)	75 (11)	59 (8.5)	45 (6.5)

(a) These data are based on a limited amount of testing and represent the lowest strength during 10,000 h of exposure at testing temperature under no load; stress applied at 34 MPa/min (5000 psi/min) to yield strength and then at strain rate of 0.05 mm/mm per min (0.05 in./in. per min) to failure. Under some conditions of temperature and time, the application of heat will adversely affect certain other properties of some alloys.

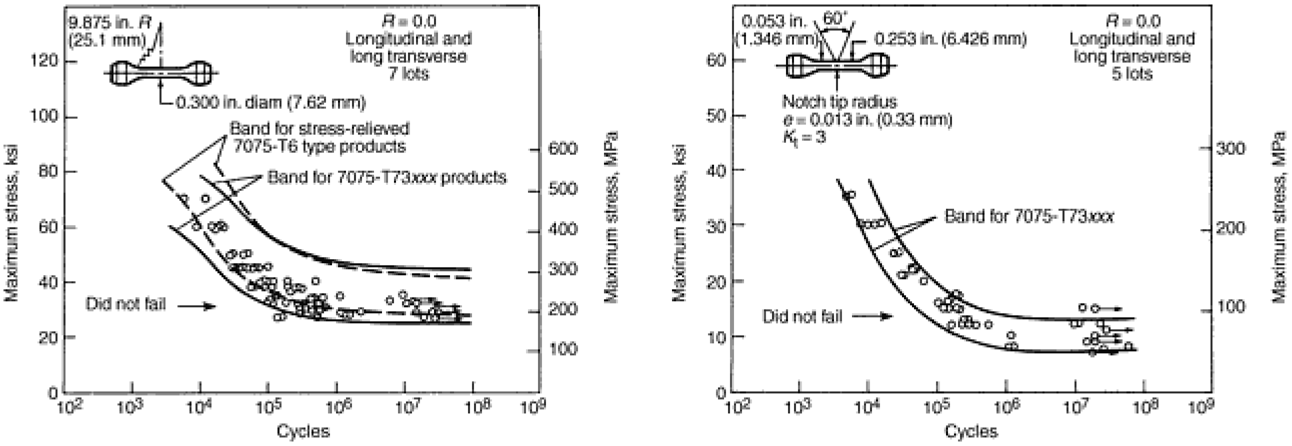


Fig. 1 Smooth and notched axial stress fatigue data for 7050-T7451 plate, 1 to 6 in. (25 to 152 mm) thick, shown in relation to bands established for 7075 wrought products in T6 and T73*xx* tempers

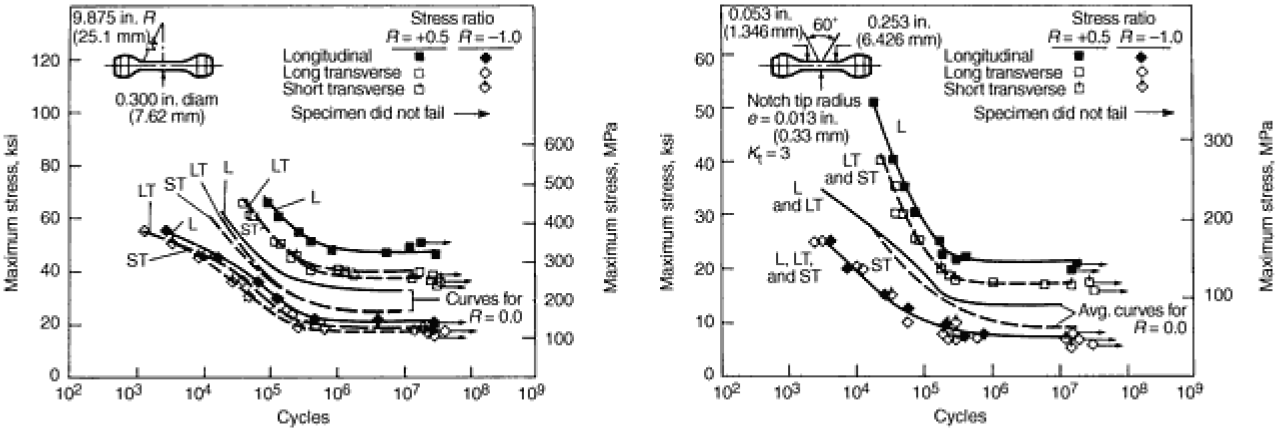


Fig. 2 Smooth and notched axial stress fatigue data for 7050-T7452 hand forgings, $4\frac{1}{2}$ × 22 × 84 in. (144 × 559 × 2133 mm)

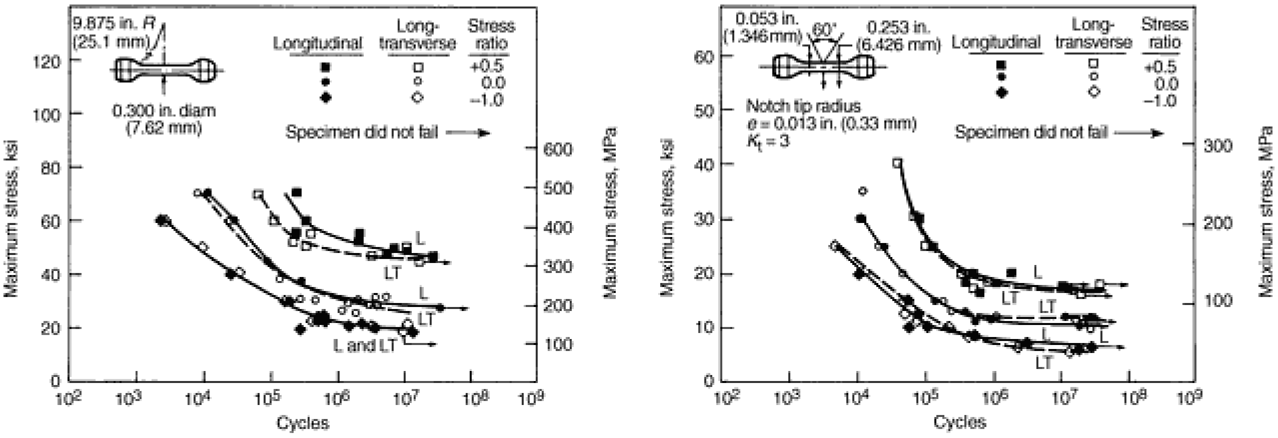


Fig. 3 Smooth and notched axial stress fatigue data for 7050-T7651x extruded shapes, 1.161 in. (29.5 mm) thick

Table 5 Effect of temperature on the yield strengths of wrought aluminum and aluminum alloys

Alloy and temper	0.2% offset yield strength[(a)], MPa (ksi), at:									
	-195 °C (-320 °F)	**-80 °C (-112 °F)**	**-30 °C (-18 °F)**	**24 °C (75 °F)**	**100 °C (212 °F)**	**150 °C (300 °F)**	**205 °C (400 °F)**	**260 °C (500 °F)**	**315 °C (600 °F)**	**370 °C (700 °F)**
1100-O	40 (6)	38 (5.5)	35 (5)	35 (5)	32 (4.6)	29 (4.2)	24 (3.5)	18 (2.6)	14 (2)	11 (1.6)
1100-H14	138 (20)	125 (18)	117 (17)	117 (17)	103 (15)	83 (12)	52 (7.5)	18 (2.6)	14 (2)	11 (1.6)
1100-H18	180 (26)	160 (23)	160 (23)	152 (22)	130 (19)	97 (14)	24 (3.5)	18 (2.6)	14 (2)	11 (1.6)
2011-T3	. . .	. . .	. . .	295 (43)	235 (34)	130 (19)	75 (11)	26 (3.8)	12 (1.8)	10 (1.4)
2014-T6, T651	495 (72)	448 (65)	427 (62)	415 (60)	393 (57)	240 (35)	90 (13)	52 (7.5)	35 (5)	24 (3.5)
2017-T4, T451	365 (53)	290 (42)	283 (41)	275 (40)	270 (39)	207 (30)	90 (13)	52 (7.5)	35 (5)	24 (3.5)
2024-T3 (sheet)	427 (62)	360 (52)	352 (51)	345 (50)	330 (48)	310 (45)	138 (20)	62 (9)	40 (6)	28 (4)
2024-T4, T351 (plate)	420 (61)	338 (49)	325 (47)	325 (47)	310 (45)	248 (36)	130 (19)	62 (9)	40 (6)	28 (4)
2024-T6, T651	470 (68)	407 (59)	400 (58)	393 (57)	372 (54)	248 (36)	130 (19)	62 (9)	40 (6)	28 (4)

2024-T81, T851	538 (78)	475 (69)	470 (68)	448 (65)	427 (62)	338 (49)	138 (20)	62 (9)	40 (6)	28 (4)
2024-T861	585 (85)	530 (77)	510 (74)	490 (71)	462 (67)	330 (48)	117 (17)	62 (9)	40 (6)	28 (4)
2117-T4	228 (33)	172 (25)	165 (24)	165 (24)	145 (21)	117 (17)	83 (12)	38 (5.5)	23 (3.3)	14 (2)
2124-T851	545 (79)	490 (71)	470 (68)	440 (64)	420 (61)	338 (49)	138 (20)	55 (8)	40 (6)	28 (4.1)
2218-T61	360 (52)	310 (45)	303 (44)	303 (44)	290 (42)	240 (35)	110 (16)	40 (6)	20 (3)	17 (2.5)
2219-T62	338 (49)	303 (44)	290 (42)	275 (40)	255 (37)	228 (33)	172 (25)	138 (20)	55 (8)	26 (3.7)
2219-T81, T851	420 (61)	372 (54)	360 (52)	345 (50)	325 (47)	275 (40)	200 (29)	160 (23)	40 (6)	26 (3.7)
2618-T61	420 (61)	380 (55)	372 (54)	372 (54)	372 (54)	303 (44)	180 (26)	62 (9)	31 (4.5)	24 (3.5)
3003-O	59 (8.5)	48 (7)	45 (6.5)	40 (6)	38 (5.5)	35 (5)	30 (4.3)	23 (3.4)	17 (2.4)	12 (1.8)
3003-H14	172 (25)	152 (22)	145 (21)	145 (21)	130 (19)	110 (16)	62 (9)	28 (4)	17 (2.4)	12 (1.8)
3003-H18	228 (33)	200 (29)	193 (28)	185 (27)	145 (21)	110 (16)	62 (9)	28 (4)	17 (2.4)	12 (1.8)
3004-O	90 (13)	75 (11)	70 (10)	70 (10)	70 (10)	70 (10)	66 (9.5)	52 (7.5)	33 (5)	20 (3)
3004-H34	235 (34)	207 (30)	200 (29)	200 (29)	200 (29)	172 (25)	103 (15)	52 (7.5)	35 (5)	20 (3)
3004-H38	295 (43)	262 (38)	248 (36)	248 (36)	248 (36)	185 (27)	103 (15)	52 (7.5)	35 (5)	20 (3)
4032-T6	330 (48)	317 (46)	317 (46)	317 (46)	303 (44)	228 (33)	62 (9)	38 (5.5)	22 (3.2)	14 (2)
5050-O	70 (10)	59 (8.5)	55 (8)	55 (8)	55 (8)	55 (8)	52 (7.5)	40 (6)	29 (4.2)	18 (2.6)
5050-H34	207 (30)	172 (25)	165 (24)	165	165 (24)	152 (22)	52 (7.5)	40 (6)	29 (4.2)	18 (2.6)

				(24)						
5050-H38	248 (36)	207 (30)	200 (29)	200 (29)	200 (29)	172 (25)	52 (7.5)	40 (6)	29 (4.2)	18 (2.6)
5052-O	110 (16)	90 (13)	90 (13)	90 (13)	90 (13)	90 (13)	75 (11)	52 (7.5)	38 (5.5)	21 (3.1)
5052-H34	248 (36)	220 (32)	215 (31)	215 (31)	215 (31)	185 (27)	103 (15)	52 (7.5)	38 (5.5)	21 (3.1)
5052-H38	303 (44)	262 (38)	255 (37)	255 (37)	248 (36)	193 (28)	103 (15)	52 (7.5)	38 (5.5)	21 (3.1)
5083-O	165 (24)	145 (21)	145 (21)	145 (21)	145 (21)	130 (19)	117 (17)	75 (11)	52 (7.5)	29 (4.2)
5086-O	130 (19)	117 (17)	117 (17)	117 (17)	117 (17)	110 (16)	103 (15)	75 (11)	52 (7.5)	29 (4.2)
5154-O	130 (19)	117 (17)	117 (17)	117 (17)	117 (17)	110 (16)	103 (15)	75 (11)	52 (7.5)	29 (4.2)
5254-O	130 (19)	117 (17)	117 (17)	117 (17)	117 (17)	110 (16)	103 (15)	75 (11)	52 (7.5)	29 (4.2)
5454-O	130 (19)	117 (17)	117 (17)	117 (17)	117 (17)	110 (16)	103 (15)	75 (11)	52 (7.5)	29 (4.2)
5454-H32	248 (36)	215 (31)	207 (30)	207 (30)	200 (29)	180 (26)	130 (19)	75 (11)	52 (7.5)	29 (4.2)
5454-H34	283 (41)	248 (36)	240 (35)	240 (35)	235 (34)	193 (28)	130 (19)	75 (11)	52 (7.5)	29 (4.2)
5456-O	180 (26)	160 (23)	160 (23)	160 (23)	152 (22)	138 (20)	117 (17)	75 (11)	52 (7.5)	29 (4.2)
5652-O	110 (16)	90 (13)	90 (13)	90 (13)	90 (13)	90 (13)	75 (11)	52 (7.5)	38 (5.5)	21 (3.1)
5652-H34	248 (36)	220 (32)	215 (31)	215 (31)	215 (31)	185 (27)	103 (15)	52 (7.5)	38 (5.5)	21 (3.1)
5652-H38	303 (44)	262 (38)	255 (37)	255 (37)	248 (36)	193 (28)	103 (15)	52 (7.5)	38 (5.5)	21 (3.1)
6053-T6, T651	. . .	. . .	. . .	220 (32)	193 (28)	165 (24)	83 (12)	28 (4)	19 (2.7)	14 (2)

6061-T6, T651	325 (47)	290 (42)	283 (41)	275 (40)	262 (38)	215 (31)	103 (15)	35 (5)	19 (2.7)	12 (1.8)
6063-T1	110 (16)	103 (15)	97 (14)	90 (13)	97 (14)	103 (15)	45 (6.5)	24 (3.5)	17 (2.5)	14 (2)
6063-T5	165 (24)	152 (22)	152 (22)	145 (21)	138 (20)	125 (18)	45 (6.5)	24 (3.5)	17 (2.5)	14 (2)
6063-T6	248 (36)	228 (33)	220 (32)	215 (31)	193 (28)	138 (20)	45 (6.5)	24 (3.5)	17 (2.5)	14 (2)
6101-T6	228 (33)	207 (30)	200 (29)	193 (28)	172 (25)	130 (19)	48 (7)	23 (3.3)	16 (2.3)	12 (1.8)
6151-T6	345 (50)	317 (46)	310 (45)	295 (43)	275 (40)	185 (27)	83 (12)	35 (5)	27 (3.9)	22 (3.2)
6262-T651	325 (47)	290 (42)	283 (41)	275 (40)	262 (38)	215 (31)	. . .	. . .	. . .	. . .
6262-T9	462 (67)	400 (58)	385 (56)	380 (55)	360 (52)	255 (37)	90 (13)	40 (6)	19 (2.7)	12 (1.8)
7075-T6, T651	635 (92)	545 (79)	517 (75)	503 (73)	448 (65)	185 (27)	90 (13)	62 (9)	45 (6.5)	32 (4.6)
7075-T73, T7351	495 (72)	462 (67)	448 (6.5)	435 (63)	400 (58)	185 (27)	90 (13)	62 (9)	45 (6.5)	32 (4.6)
7178-T6, T651	648 (94)	580 (84)	558 (81)	538 (78)	470 (68)	185 (27)	83 (12)	62 (9)	48 (7)	35 (5.5)
7178-T76, T7651	615 (89)	538 (78)	525 (76)	503 (73)	440 (64)	185 (27)	83 (12)	62 (9)	48 (7)	38 (5.5)

(a) These data are based on a limited amount of testing and represent the lowest strength during 10,000 h of exposure at testing temperature under no load; stress applied at 34 MPa/min (5000 psi/min) to yield strength and then at strain rate of 0.05 mm/mm per min (0.05 in./in. per min) to failure. Under some conditions of temperature and time, the application of heat will adversely affect certain other properties of some alloys.

Table 6 Effect of temperature on the elongation of wrought aluminum and aluminum alloys

Alloy and temper	Elongation(a) in 50 mm (2 in.), %, at:									
	-195 °C (-320 °F)	**-80 °C (-112 °F)**	**-30 °C (-18 °F)**	**24 °C (75 °F)**	**100 °C (212 °F)**	**150 °C (300 °F)**	**205 °C (400 °F)**	**260 °C (500 °F)**	**315 °C (600 °F)**	**370 °C (700 °F)**
1100-O	50	43	40	40	45	55	65	75	80	85

1100-H14	45	24	20	20	20	23	26	75	80	85
1100-H18	30	16	15	15	15	20	65	75	80	85
2011-T3	. . .	. . .	. . .	15	16	25	35	45	90	125
2014-T6, T651	14	13	13	13	15	20	28	52	65	72
2017-T4, T451	28	24	23	22	18	15	35	45	65	70
2024-T3 (sheet)	18	17	17	17	16	11	23	55	75	100
2024-T4, T351 (plate)	19	19	19	19	19	17	27	55	75	100
2024-T6, T651	11	10	10	10	10	17	27	55	75	100
2024-T81, T851	8	7	7	7	8	11	23	55	75	100
2024-T861	5	5	5	5	6	11	28	55	75	100
2117-T4	30	29	28	27	16	20	35	55	80	110
2124-T851	9	8	8	9	9	13	28	60	75	100
2218-T61	15	14	13	13	15	17	30	70	85	100
2219-T62	16	13	12	12	14	17	20	21	40	75
2219-T81, T851	15	13	12	12	15	17	20	21	55	75
2618-T61	12	11	10	10	10	14	24	50	80	120
3003-O	46	42	41	40	43	47	60	65	70	70
3003-H14	30	18	16	16	16	16	20	60	70	70

3003-H18	23	11	10	10	10	11	18	60	70	70
3004-O	38	30	26	25	25	35	55	70	80	90
3004-H34	26	16	13	12	13	22	35	55	80	90
3004-H38	20	10	7	6	7	15	30	50	80	90
4032-T6	11	10	9	9	9	9	30	50	70	90
5052-O	46	35	32	30	36	50	60	80	110	130
5052-H34	28	21	18	16	18	27	45	80	110	130
5052-H38	25	18	15	14	16	24	45	80	110	130
5083-O	36	30	27	25	36	50	60	80	110	130
5086-O	46	35	32	30	36	50	60	80	110	130
5154-O	46	35	32	30	36	50	60	80	110	130
5254-O	46	35	32	30	36	50	60	80	110	130
5454-O	39	30	27	25	31	50	60	80	110	130
5454-H32	32	23	20	18	20	37	45	80	110	130
5454-H34	30	21	18	16	18	32	45	80	110	130
5456-O	32	25	22	20	31	50	60	80	110	130
5652-O	46	35	32	30	30	50	60	80	110	130
5652-H34	28	21	18	16	18	27	45	80	110	130
5652-H38	25	18	15	14	16	24	45	80	110	130
6053-T6, T651	. . .	. . .	. . .	13	13	13	25	70	80	90

6061-T6, T651	22	18	17	17	18	20	28	60	85	95
6063-T1	44	36	34	33	18	20	40	75	80	105
6063-T5	28	24	23	22	18	20	40	75	80	105
6063-T6	24	20	19	18	15	20	40	75	80	105
6101-T6	24	20	19	19	20	20	40	80	100	105
6151-T6	20	17	17	17	17	20	30	50	43	35
6262-T651	22	18	17	17	18	20	. . .	. . .	. . .	. . .
6262-T9	14	10	10	10	10	14	34	48	85	95
7075-T6, T651	9	11	11	11	14	30	55	65	70	70
7075-T73, T7351	14	14	13	13	15	30	55	65	70	70
7178-T6, T651	5	8	9	11	14	40	70	76	80	80
7178-T76, T7651	10	10	10	11	17	40	70	76	80	80

(a) These data are based on a limited amount of testing and represent the lowest strength during 10,000 h of exposure at testing temperature under no load; stress applied at 34 MPa/min (5000 psi/min) to yield strength and then at strain rate of 0.05 mm/mm per min (0.05 in./in. per min) to failure. Under some conditions of temperature and time, the application of heat will adversely affect certain other properties of some alloys.

Table 7 Mechanical property limits for non-heat-treatable aluminum alloy sheet and plate

Alloy and temper	Specified thickness[a]		Tensile strength				Yield strength				Elongation (min)[c], %
			Minimum		**Maximum**		**Minimum[b]**		**Maximum**		
	mm	**in.**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	
1060-O	0.15-0.48	0.006-0.019	55	8.0	97	14.0	17	2.5	. . .	. . .	15
	0.51-1.27	0.020-0.050	55	8.0	97	14.0	17	2.5	. . .	. . .	22

	1.30-76.20	0.051-3.000	55	8.0	97	14.0	17	2.5	. . .	. . .	25
1060-H12(d)	0.43-1.27	0.017-0.050	76	11.0	110	16.0	62	9.0	. . .	. . .	6
	1.30-50.80	0.051-2.000	76	11.0	110	16.0	62	9.0	. . .	. . .	12
1060-H14(d)	0.23-0.48	0.009-0.019	83	12.0	117	17.0	69	10.0	. . .	. . .	1
	0.51-1.27	0.020-0.050	83	12.0	117	17.0	69	10.0	. . .	. . .	5
	1.30-25.40	0.051-1.000	83	12.0	117	17.0	69	10.0	. . .	. . .	10
1060-H16(d)	0.15-0.48	0.006-0.019	97	14.0	131	19.0	76	11.0	. . .	. . .	1
	0.51-1.27	0.020-0.050	97	14.0	131	19.0	76	11.0	. . .	. . .	4
	1.30-4.11	0.051-0.162	97	14.0	131	19.0	76	11.0	. . .	. . .	5
1060-H18(d)	0.15-0.48	0.006-0.019	110	16.0	. . .	. . .	83	12.0	. . .	. . .	1
	0.51-1.27	0.020-0.050	110	16.0	. . .	. . .	83	12.0	. . .	. . .	3
	1.30-3.25	0.051-0.128	110	16.0	. . .	. . .	83	12.0	. . .	. . .	4
1060-H112	6.35-12.67	0.250-0.499	76	11.0	. . .	. . .	. . .	. . .	. . .	. . .	10
	12.70-25.40	0.500-1.000	69	10.0	. . .	. . .	. . .	. . .	. . .	. . .	20
	25.42-76.20	1.001-3.000	62	9.0	. . .	. . .	. . .	. . .	. . .	. . .	25
1100-O	0.15-0.48	0.006-0.019	76	11.0	107	15.5	24	3.5	. . .	. . .	15
	0.51-0.79	0.020-0.031	76	11.0	107	15.5	24	3.5	. . .	. . .	20
	0.81-1.27	0.032-0.050	76	11.0	107	15.5	24	3.5	. . .	. . .	25
	1.30-6.32	0.051-0.249	76	11.0	107	15.5	24	3.5	. . .	. . .	30
	6.35-76.20	0.250-3.000	76	11.0	107	15.5	24	3.5	. . .	. . .	28
1100-H12(d)	0.43-0.48	0.017-0.019	97	14.0	131	19.0	76	11.0	. . .	. . .	3

	0.51-0.79	0.020-0.031	97	14.0	131	19.0	76	11.0	. . .	. . .	4
	0.81-1.27	0.032-0.050	97	14.0	131	19.0	76	11.0	. . .	. . .	6
	1.30-2.87	0.051-0.113	97	14.0	131	19.0	76	11.0	. . .	. . .	8
	2.90-12.67	0.114-0.499	97	14.0	131	19.0	76	11.0	. . .	. . .	9
	12.70-50.80	0.500-2.000	97	14.0	131	19.0	76	11.0	. . .	. . .	12
1100-H14(d)	0.23-0.30	0.009-0.012	110	16.0	145	21.0	97	14.0	. . .	. . .	1
	0.33-0.48	0.013-0.019	110	16.0	145	21.0	97	14.0	. . .	. . .	2
	0.51-0.79	0.020-0.031	110	16.0	145	21.0	97	14.0	. . .	. . .	3
	0.81-1.27	0.032-0.050	110	16.0	145	21.0	97	14.0	. . .	. . .	4
	1.30-2.87	0.051-0.113	110	16.0	145	21.0	97	14.0	. . .	. . .	5
	2.90-12.67	0.114-0.499	110	16.0	145	21.0	97	14.0	. . .	. . .	6
	12.70-25.40	0.500-1.000	110	16.0	145	21.0	97	14.0	. . .	. . .	10
1100-H16(d)	0.15-0.48	0.006-0.019	131	19.0	165	24.0	117	17.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	131	19.0	165	24.0	117	17.0	. . .	. . .	2
	0.81-1.27	0.032-0.050	131	19.0	165	24.0	117	17.0	. . .	. . .	3
	1.30-4.11	0.051-0.162	131	19.0	165	24.0	117	17.0	. . .	. . .	4
1100-H18	0.15-0.48	0.006-0.019	152	22.0	. . .	. . .	. . .	. . .	. . .	. . .	1
	0.51-0.79	0.020-0.031	152	22.0	. . .	. . .	. . .	. . .	. . .	. . .	2
	0.81-1.27	0.032-0.050	152	22.0	. . .	. . .	. . .	. . .	. . .	. . .	3
	1.30-3.25	0.051-0.128	152	22.0	. . .	. . .	. . .	. . .	. . .	. . .	4
1100-H112	6.35-12.67	0.250-0.499	90	13.0	. . .	. . .	48	7.0	. . .	. . .	9

	12.70-50.80	0.500-2.000	83	12.0	. . .	. . .	34	5.0	. . .	. . .	14
	50.83-76.20	2.001-3.000	79	11.5	. . .	. . .	28	4.0	. . .	. . .	20
1350-O	0.15-0.48	0.006-0.019	55	8.0	97	14.0	. . .	. . .	. . .	. . .	15
	0.51-0.79	0.020-0.031	55	8.0	97	14.0	. . .	. . .	. . .	. . .	20
	0.81-1.27	0.032-0.050	55	8.0	97	14.0	. . .	. . .	. . .	. . .	25
	1.29-6.32	0.051-0.249	55	8.0	97	14.0	. . .	. . .	. . .	. . .	30
	6.35-76.20	0.250-3.000	55	8.0	97	14.0	. . .	. . .	. . .	. . .	28
1350-H12	0.43-0.48	0.017-0.019	83	12.0	117	17.0	. . .	. . .	. . .	. . .	3
	0.51-0.79	0.020-0.031	83	12.0	117	17.0	. . .	. . .	. . .	. . .	4
	0.81-1.27	0.032-0.050	83	12.0	117	17.0	. . .	. . .	. . .	. . .	6
	1.29-2.87	0.051-0.113	83	12.0	117	17.0	. . .	. . .	. . .	. . .	8
	2.90-12.67	0.114-0.499	83	12.0	117	17.0	. . .	. . .	. . .	. . .	9
	12.70-50.80	0.500-2.000	83	12.0	117	17.0	. . .	. . .	. . .	. . .	12
1350-H14	0.23-0.30	0.009-0.012	97	14.0	131	19.0	. . .	. . .	. . .	. . .	1
	0.33-0.48	0.013-0.019	97	14.0	131	19.0	. . .	. . .	. . .	. . .	2
	0.51-0.79	0.020-0.031	97	14.0	131	19.0	. . .	. . .	. . .	. . .	3
	0.81-1.27	0.032-0.050	97	14.0	131	19.0	. . .	. . .	. . .	. . .	4
	1.29-2.87	0.051-0.113	97	14.0	131	19.0	. . .	. . .	. . .	. . .	5
	2.90-12.67	0.114-0.499	97	14.0	131	19.0	. . .	. . .	. . .	. . .	6
	12.70-25.40	0.500-1.000	97	14.0	131	19.0	. . .	. . .	. . .	. . .	10
1350-H16	0.15-0.48	0.006-0.019	110	16.0	145	21.0	. . .	. . .	. . .	. . .	1

	0.51-0.79	0.020-0.031	110	16.0	145	21.0	. . .	. . .	. . .	. . .	2
	0.81-1.27	0.032-0.050	110	16.0	145	21.0	. . .	. . .	. . .	. . .	3
	1.29-4.11	0.051-0.162	110	16.0	145	21.0	. . .	. . .	. . .	. . .	4
1350-H18	0.15-0.48	0.006-0.019	124	18.0	. . .	. . .	. . .	. . .	. . .	. . .	1
	0.51-0.79	0.020-0.031	124	18.0	. . .	. . .	. . .	. . .	. . .	. . .	2
	0.81-1.27	0.032-0.050	124	18.0	. . .	. . .	. . .	. . .	. . .	. . .	3
	1.29-3.25	0.051-0.128	124	18.0	. . .	. . .	. . .	. . .	. . .	. . .	4
1350-H112	6.35-12.67	0.250-0.499	76	11.0	. . .	. . .	. . .	. . .	. . .	. . .	10
	12.70-25.40	0.500-1.000	69	10.0	. . .	. . .	. . .	. . .	. . .	. . .	16
	25.42-38.1	1.001-1.500	62	9.0	. . .	. . .	. . .	. . .	. . .	. . .	22
3003-O	0.15-0.18	0.006-0.007	97	14.0	131	19.0	34	5.0	. . .	. . .	14
	0.20-0.30	0.008-0.012	97	14.0	131	19.0	34	5.0	. . .	. . .	18
	0.33-0.79	0.013-0.031	97	14.0	131	19.0	34	5.0	. . .	. . .	20
	0.81-1.27	0.032-0.050	97	14.0	131	19.0	34	5.0	. . .	. . .	23
	1.30-6.32	0.051-0.249	97	14.0	131	19.0	34	5.0	. . .	. . .	25
	6.35-76.20	0.250-3.000	97	14.0	131	19.0	34	5.0	. . .	. . .	23
3003-H12(d)	0.43-0.48	0.017-0.019	117	17.0	159	23.0	83	12.0	. . .	. . .	3
	0.51-0.79	0.020-0.031	117	17.0	159	23.0	83	12.0	. . .	. . .	4
	0.81-1.27	0.032-0.050	117	17.0	159	23.0	83	12.0	. . .	. . .	5
	1.30-2.87	0.051-0.113	117	17.0	159	23.0	83	12.0	. . .	. . .	6
	2.90-4.09	0.114-0.161	117	17.0	159	23.0	83	12.0	. . .	. . .	7

	4.11-6.32	0.162-0.249	117	17.0	159	23.0	83	12.0	. . .	. . .	8
	6.35-12.67	0.250-0.499	117	17.0	159	23.0	83	12.0	. . .	. . .	9
	12.70-50.80	0.500-2.000	117	17.0	159	23.0	83	12.0	. . .	. . .	10
3003-H14(d)	0.23-0.30	0.009-0.012	138	20.0	179	26.0	117	17.0	. . .	. . .	1
	0.33-0.48	0.013-0.019	138	20.0	179	26.0	117	17.0	. . .	. . .	2
	0.51-0.79	0.020-0.031	138	20.0	179	26.0	117	17.0	. . .	. . .	3
	0.81-1.27	0.032-0.050	138	20.0	179	26.0	117	17.0	. . .	. . .	4
	1.30-2.87	0.051-0.113	138	20.0	179	26.0	117	17.0	. . .	. . .	5
	2.90-4.09	0.114-0.161	138	20.0	179	26.0	117	17.0	. . .	. . .	6
	4.11-6.32	0.162-0.249	138	20.0	179	26.0	117	17.0	. . .	. . .	7
	6.35-12.67	0.250-0.499	138	20.0	179	26.0	117	17.0	. . .	. . .	8
	12.70-25.40	0.500-1.000	138	20.0	179	26.0	117	17.0	. . .	. . .	10
3003-H16(d)	0.15-0.48	0.006-0.019	165	24.0	207	30.0	145	21.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	165	24.0	207	30.0	145	21.0	. . .	. . .	2
	0.81-1.27	0.032-0.050	165	24.0	207	30.0	145	21.0	. . .	. . .	3
	1.30-4.11	0.051-0.162	165	24.0	207	30.0	145	21.0	. . .	. . .	4
3003-H18(d)	0.15-0.48	0.006-0.019	186	27.0	. . .	. . .	165	24.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	186	27.0	. . .	. . .	165	24.0	. . .	. . .	2
	0.81-1.27	0.032-0.050	186	27.0	. . .	. . .	165	24.0	. . .	. . .	3
	1.30-3.25	0.051-0.128	186	27.0	. . .	. . .	165	24.0	. . .	. . .	4
3003-H112	6.35-12.67	0.250-0.499	117	17.0	. . .	. . .	69	10.0	. . .	. . .	8

	12.70-50.80	0.500-2.000	103	15.0	. . .	. . .	41	6.0	. . .	. . .	12
	50.83-76.20	2.001-3.000	100	14.5	. . .	. . .	41	6.0	. . .	. . .	18
3004-O	0.15-0.18	0.006-0.007	152	22.0	200	29.0	59	8.5	. . .	. . .	. . .
	0.20-0.48	0.008-0.019	152	22.0	200	29.0	59	8.5	. . .	. . .	10
	0.51-0.79	0.020-0.031	152	22.0	200	29.0	59	8.5	. . .	. . .	14
	0.81-1.27	0.032-0.050	152	22.0	200	29.0	59	8.5	. . .	. . .	16
	1.30-6.32	0.051-0.249	152	22.0	200	29.0	59	8.5	. . .	. . .	18
	6.35-76.20	0.250-3.000	152	22.0	200	29.0	59	8.5	. . .	. . .	16
3004-H32(d)	0.43-0.48	0.017-0.019	193	28.0	241	35.0	145	21.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	193	28.0	241	35.0	145	21.0	. . .	. . .	3
	0.81-1.27	0.032-0.050	193	28.0	241	35.0	145	21.0	. . .	. . .	4
	1.30-2.87	0.051-0.113	193	28.0	241	35.0	145	21.0	. . .	. . .	5
	2.90-50.80	0.114-2.000	193	28.0	241	35.0	145	21.0	. . .	. . .	6
3004-H34(d)	0.23-0.48	0.009-0.019	221	32.0	262	38.0	172	25.0	. . .	. . .	1
	0.51-1.27	0.020-0.050	221	32.0	262	38.0	172	25.0	. . .	. . .	3
	1.30-2.87	0.051-0.113	221	32.0	262	38.0	172.	25.0	. . .	. . .	4
	2.90-25.40	0.114-1.000	221	32.0	262	38.0	172	25.0	. . .	. . .	5
3004-H36(d)	0.15-0.18	0.006-0.007	241	35.0	283	41.0	193	28.0	. . .	. . .	. . .
	0.20-0.48	0.008-0.019	241	35.0	283	41.0	193	28.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	241	35.0	283	41.0	193	28.0	. . .	. . .	2
	0.81-1.27	0.032-0.050	241	35.0	283	41.0	193	28.0	. . .	. . .	3

	1.30-4.11	0.051-0.162	241	35.0	283	41.0	193	28.0	. . .	. . .	4
3004-H38[(d)]	0.15-0.18	0.006-0.007	262	38.0	. . .	. . .	214	31.0	. . .	. . .	. . .
	0.20-0.48	0.008-0.019	262	38.0	. . .	. . .	214	31.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	262	38.0	. . .	. . .	214	31.0	. . .	. . .	2
	0.81-1.27	0.032-0.050	262	38.0	. . .	. . .	214	31.0	. . .	. . .	3
	1.30-3.25	0.051-0.128	262	38.0	. . .	. . .	214	31.0	. . .	. . .	4
3004-H112	6.35-76.20	0.250-3.000	159	23.0	. . .	. . .	62	9.0	. . .	. . .	7
3005-O	0.15-0.18	0.006-0.007	117	17.0	165	24.0	45	6.5	. . .	. . .	10
	0.20-0.30	0.008-0.012	117	17.0	165	24.0	45	6.5	. . .	. . .	12
	0.33-0.48	0.013-0.019	117	17.0	165	24.0	45	6.5	. . .	. . .	14
	0.51-0.79	0.020-0.031	117	17.0	165	24.0	45	6.5	. . .	. . .	16
	0.81-1.27	0.032-0.050	117	17.0	165	24.0	45	6.5	. . .	. . .	18
	1.29-6.32	0.051-0.249	117	17.0	165	24.0	45	6.5	. . .	. . .	20
3005-H12	0.43-0.48	0.017-0.019	138	20.0	186	27.0	17	17.0	. . .	. . .	1
	0.51-1.27	0.020-0.050	138	20.0	186	27.0	117	17.0	. . .	. . .	2
	1.29-2.87	0.051-0.113	138	20.0	186	27.0	117	17.0	. . .	. . .	3
	2.90-4.09	0.114-0.161	138	20.0	186	27.0	117	17.0	. . .	. . .	4
	4.11-6.32	0.162-0.249	138	20.0	186	27.0	117	17.0	. . .	. . .	5
3005-H14	0.23-0.79	0.009-0.031	165	24.0	214	31.0	145	21.0	. . .	. . .	1
	0.81-1.27	0.032-0.050	165	24.0	214	31.0	145	21.0	. . .	. . .	2
	1.29-2.87	0.051-0.113	165	24.0	214	31.0	145	21.0	. . .	. . .	3

	2.90-6.32	0.114-0.249	165	24.0	214	31.0	145	21.0	. . .	. . .	4
3005-H16	0.15-0.79	0.006-0.031	193	28.0	241	35.0	172	25.0	. . .	. . .	1
	0.81-2.87	0.032-0.113	193	28.0	241	35.0	172	25.0	. . .	. . .	2
	2.90-6.32	0.114-0.162	193	28.0	241	35.0	172	25.0	. . .	. . .	3
3005-H18	0.15-0.79	0.006-0.031	221	32.0	. . .	. . .	200	29.0	. . .	. . .	1
	0.81-3.25	0.032-0.128	221	32.0	. . .	. . .	200	29.0	. . .	. . .	2
3005-H19	0.15-0.30	0.006-0.012	234	34.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	0.33-1.60	0.013-0.063	234	34.0	. . .	. . .	. . .	. . .	. . .	. . .	1
3005-H25	0.15-0.48	0.006-0.019	179	26.0	234	34.0	152	22.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	179	26.0	234	34.0	152	22.0	. . .	. . .	2
	0.81-1.27	0.032-0.050	179	26.0	234	34.0	152	22.0	. . .	. . .	3
	1.29-2.03	0.051-0.080	179	26.0	234	34.0	152	22.0	. . .	. . .	4
3005-H26	0.15-0.48	0.006-0.019	193	28.0	248	36.0	165	24.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	193	28.0	248	36.0	165	24.0	. . .	. . .	2
	0.81-1.29	0.032-0.050	193	28.0	248	36.0	165	24.0	. . .	. . .	3
	1.29-2.03	0.051-0.080	193	28.0	248	36.0	165	24.0	. . .	. . .	4
3005-H27	0.15-0.48	0.006-0.019	203	29.5	259	37.5	179	26.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	203	29.5	259	37.5	179	26.0	. . .	. . .	2
	0.81-1.27	0.032-0.050	203	29.5	259	37.5	179	26.0	. . .	. . .	3
	1.29-2.03	0.051-0.080	203	29.5	259	37.5	179	26.0	. . .	. . .	4
3005-H28	0.15-0.48	0.006-0.019	214	31.0	. . .	. . .	186	27.0	. . .	. . .	1

	0.51-0.79	0.020-0.031	214	31.0	. . .	. . .	186	27.0	. . .	. . .	2
	0.81-1.27	0.032-0.050	214	31.0	. . .	. . .	186	27.0	. . .	. . .	3
	1.29-2.03	0.051-0.080	214	31.0	. . .	. . .	186	27.0	. . .	. . .	4
3105-O	0.33-0.48	0.013-0.019	97	14.0	145	21.0	34	5.0	. . .	. . .	16
	0.51-0.79	0.020-0.031	97	14.0	145	21.0	34	5.0	. . .	. . .	18
	0.81-2.03	0.032-0.080	97	14.0	145	21.0	34	5.0	. . .	. . .	20
3105-H12	0.43-0.48	0.017-0.019	131	19.0	179	26.0	103	15.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	131	19.0	179	26.0	103	15.0	. . .	. . .	1
	0.81-1.27	0.032-0.050	131	19.0	179	26.0	103	15.0	. . .	. . .	2
	1.29-2.03	0.051-0.080	131	19.0	179	26.0	103	15.0	. . .	. . .	3
3105-H14	0.33-0.48	0.013-0.019	152	22.0	200	29.0	124	18.0	. . .	. . .	1
	0.51-0.79	0.020-0.031	152	22.0	200	29.0	124	18.0	. . .	. . .	1
	0.81-1.27	0.032-0.050	152	22.0	200	29.0	124	18.0	. . .	. . .	2
	1.29-2.03	0.051-0.080	152	22.0	200	29.0	124	18.0	. . .	. . .	2
3105-H16	0.33-0.79	0.013-0.031	172	25.0	221	32.0	145	21.0	. . .	. . .	1
	0.81-1.27	0.032-0.050	172	25.0	221	32.0	145	21.0	. . .	. . .	2
	1.29-2.03	0.051-0.080	172	25.0	221	32.0	145	21.0	. . .	. . .	2
3105-H18	0.33-0.79	0.013-0.031	193	28.0	. . .	. . .	165	24.0	. . .	. . .	1
	0.81-1.27	0.032-0.050	193	28.0	. . .	. . .	165	24.0	. . .	. . .	1
	1.29-2.03	0.051-0.080	193	28.0	. . .	. . .	165	24.0	. . .	. . .	2
3105-H25	0.33-0.48	0.013-0.019	159	23.0	. . .	. . .	131	19.0	. . .	. . .	2

	0.51-0.79	0.020-0.031	159	23.0	. . .	. . .	131	19.0	. . .	. . .	3
	0.81-1.27	0.032-0.050	159	23.0	. . .	. . .	131	19.0	. . .	. . .	4
	1.29-2.03	0.051-0.080	159	23.0	. . .	. . .	131	19.0	. . .	. . .	6
5005-O	0.15-0.18	0.006-0.007	103	15.0	145	21.0	34	5.0	. . .	. . .	12
	0.20-0.30	0.008-0.012	103	15.0	145	21.0	34	5.0	. . .	. . .	14
	0.33-0.48	0.013-0.019	103	15.0	145	21.0	34	5.0	. . .	. . .	16
	0.51-0.79	0.020-0.031	103	15.0	145	21.0	34	5.0	. . .	. . .	18
	0.81-1.27	0.032-0.050	103	15.0	145	21.0	34	5.0	. . .	. . .	20
	1.29-2.87	0.051-0.113	103	15.0	145	21.0	34	5.0	. . .	. . .	21
	2.90-6.32	0.114-0.249	103	15.0	145	21.0	34	5.0	. . .	. . .	22
	6.35-76.2	0.250-3.000	103	15.0	145	21.0	34	5.0	. . .	. . .	22
5005-H12	0.43-0.48	0.017-0.019	124	18.0	165	24.0	97	14.0	. . .	. . .	2
	0.51-0.79	0.020-0.031	124	18.0	165	24.0	97	14.0	. . .	. . .	3
	0.81-1.27	0.032-0.050	124	18.0	165	24.0	97	14.0	. . .	. . .	4
	1.29-2.87	0.051-0.113	124	18.0	165	24.0	97	14.0	. . .	. . .	6
	2.89-4.09	0.114-0.161	124	18.0	165	24.0	97	14.0	. . .	. . .	7
	4.11-6.32	0.162-0.249	124	18.0	165	24.0	97	14.0	. . .	. . .	8
	6.35-12.67	0.250-0.499	124	18.0	165	24.0	97	14.0	. . .	. . .	9
	12.70-50.80	0.500-2.000	124	18.0	165	24.0	97	14.0	. . .	. . .	10
5005-H14	0.23-0.79	0.009-0.031	145	21.0	186	27.0	117	17.0	. . .	. . .	1
	0.81-1.27	0.032-0.050	145	21.0	186	27.0	117	17.0	. . .	. . .	2

	1.29-2.87	0.051-0.113	145	21.0	186	27.0	117	17.0	. . .	. . .	3
	2.90-4.09	0.114-0.161	145	21.0	186	27.0	117	17.0	. . .	. . .	5
	4.11-6.32	0.162-0.249	145	21.0	186	27.0	117	17.0	. . .	. . .	6
	6.35-12.67	0.250-0.499	145	21.0	186	27.0	117	17.0	. . .	. . .	8
	12.70-25.40	0.500-1.000	145	21.0	186	27.0	117	17.0	. . .	. . .	10
5005-H16	0.15-0.79	0.006-0.031	165	24.0	207	30.0	138	20.0	. . .	. . .	1
	0.81-1.27	0.032-0.050	165	24.0	207	30.0	138	20.0	. . .	. . .	2
	1.29-4.11	0.051-0.162	165	24.0	207	30.0	138	20.0	. . .	. . .	3
5005-H18	0.15-0.79	0.006-0.031	186	27.0	. . .	. . .	. . .	. . .	. . .	. . .	1
	0.81-1.27	0.032-0.050	186	27.0	. . .	. . .	. . .	. . .	. . .	. . .	2
	1.29-3.25	0.051-0.128	186	27.0	. . .	. . .	. . .	. . .	. . .	. . .	3
5005-H32(d)	0.43-0.48	0.017-0.019	117	17.0	159	23.0	83	12.0	. . .	. . .	3
	0.51-0.79	0.020-0.031	117	17.0	159	23.0	83	12.0	. . .	. . .	4
	0.81-1.27	0.032-0.050	117	17.0	159	23.0	83	12.0	. . .	. . .	5
	1.29-2.87	0.051-0.113	117	17.0	159	23.0	83	12.0	. . .	. . .	7
	2.90-4.09	0.114-0.161	117	17.0	159	23.0	83	12.0	. . .	. . .	8
	4.11-6.32	0.162-0.249	117	17.0	159	23.0	83	12.0	. . .	. . .	9
	6.35-50.80	0.250-2.000	117	17.0	159	23.0	83	12.0	. . .	. . .	10
5005-H34(d)	0.23-0.30	0.009-0.012	138	20.0	179	26.0	103	15.0	. . .	. . .	2
	0.33-0.79	0.013-0.031	138	20.0	179	26.0	103	15.0	. . .	. . .	3
	0.81-1.27	0.032-0.050	138	20.0	179	26.0	103	15.0	. . .	. . .	4

	1.29-2.87	0.051-0.113	138	20.0	179	26.0	103	15.0	. . .	. . .	5
	2.90-4.09	0.114-0.161	138	20.0	179	26.0	103	15.0	. . .	. . .	6
	4.11-6.32	0.162-0.249	138	20.0	179	26.0	103	15.0	. . .	. . .	7
	6.35-12.67	0.250-0.499	138	20.0	179	26.0	103	15.0	. . .	. . .	8
	12.70-25.40	0.500-1.00	138	20.0	179	26.0	103	15.0	. . .	. . .	10
5005-H36(d)	0.15-0.18	0.006-0.007	159	23.0	200	29.0	124	18.0	. . .	. . .	1
	0.20-0.48	0.008-0.019	159	23.0	200	29.0	124	18.0	. . .	. . .	2
	0.51-0.79	0.020-0.031	159	23.0	200	29.0	124	18.0	. . .	. . .	3
	0.81-4.11	0.032-0.162	159	23.0	200	29.0	124	18.0	. . .	. . .	4
5005-H38	0.15-0.30	0.006-0.012	179	26.0	. . .	. . .	. . .	. . .	. . .	. . .	1
	0.33-0.48	0.013-0.019	179	26.0	. . .	. . .	. . .	. . .	. . .	. . .	2
	0.51-0.79	0.020-0.031	179	26.0	. . .	. . .	. . .	. . .	. . .	. . .	3
	0.81-3.25	0.032-0.128	179	26.0	. . .	. . .	. . .	. . .	. . .	. . .	4
5005-H39	0.15-1.60	0.006-0.063	193	28.0	. . .	. . .	. . .	. . .	. . .	. . .	1
5005-H112	6.35-12.67	0.250-0.499	117	17.0	. . .	. . .	. . .	. . .	. . .	. . .	8
	12.70-50.80	0.500-2.000	103	15.0	. . .	. . .	. . .	. . .	. . .	. . .	12
	50.82-76.20	2.001-3.000	100	14.5	. . .	. . .	. . .	. . .	. . .	. . .	18
5050-O	0.15-0.18	0.006-0.007	124	18.0	165	24.0	41	6.0	. . .	. . .	. . .
	0.20-0.48	0.008-0.019	124	18.0	165	24.0	41	6.0	. . .	. . .	16
	0.51-0.79	0.020-0.031	124	18.0	165	24.0	41	6.0	. . .	. . .	18
	0.81-2.87	0.032-0.113	124	18.0	165	24.0	41	6.0	. . .	. . .	20

	2.90-6.32	0.114-0.249	124	18.0	165	24.0	41	6.0	. . .	. . .	22
	6.35-76.20	0.250-3.000	124	18.0	165	24.0	41	6.0	. . .	. . .	20
5050-H32(d)	0.43-1.27	0.017-0.050	152	22.0	193	28.0	110	16.0	. . .	. . .	4
	1.29-6.32	0.051-0.249	152	22.0	193	28.0	110	16.0	. . .	. . .	6
5050-H34(d)	0.23-0.79	0.009-0.031	172	25.0	214	31.0	138	20.0	. . .	. . .	3
	0.81-1.27	0.032-0.050	172	25.0	214	31.0	138	20.0	. . .	. . .	4
	1.29-6.32	0.051-0.249	172	25.0	214	31.0	138	20.0	. . .	. . .	5
5050-H36(d)	0.15-0.48	0.006-0.019	186	27.0	228	33.0	152	22.0	. . .	. . .	2
	0.51-1.27	0.020-0.050	186	27.0	228	33.0	152	22.0	. . .	. . .	3
	1.29-4.11	0.051-0.162	186	27.0	228	33.0	152	22.0	. . .	. . .	4
5050-H38	0.15-0.18	0.006-0.007	200	29.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	0.20-0.79	0.008-0.031	200	29.0	. . .	. . .	. . .	. . .	. . .	. . .	2
	0.81-1.27	0.032-0.050	200	29.0	. . .	. . .	. . .	. . .	. . .	. . .	3
	1.29-3.25	0.051-0.128	200	29.0	. . .	. . .	. . .	. . .	. . .	. . .	4
5050-H39	0.15-1.60	0.006-0.063	214	31.0	. . .	. . .	. . .	. . .	. . .	. . .	1
5050-H112	6.35-76.20	0.250-3.000	138	20.0	. . .	. . .	55	8.0	. . .	. . .	12
5052-O	0.15-0.18	0.006-0.007	172	25.0	214	31.0	65	9.5	. . .	. . .	. . .
	0.20-0.30	0.008-0.012	172	25.0	214	31.0	65	9.5	. . .	. . .	14
	0.33-0.48	0.013-0.019	172	25.0	214	31.0	65	9.5	. . .	. . .	15
	0.51-0.79	0.020-0.031	172	25.0	214	31.0	65	9.5	. . .	. . .	16
	0.81-1.27	0.032-0.050	172	25.0	214	31.0	65	9.5	. . .	. . .	18

	1.30-2.87	0.051-0.113	172	25.0	214	31.0	65	9.5	. . .	. . .	19
	2.90-6.32	0.114-0.249	172	25.0	214	31.0	65	9.5	. . .	. . .	20
	6.35-76.20	0.250-3.000	172	25.0	214	31.0	65	9.5	. . .	. . .	18
5052-H32[(d)]	0.43-0.48	0.017-0.019	214	31.0	262	38.0	159	23.0	. . .	. . .	4
	0.51-1.27	0.020-0.050	214	31.0	262	38.0	159	23.0	. . .	. . .	5
	1.30-2.87	0.051-0.113	214	31.0	262	38.0	159	23.0	. . .	. . .	7
	2.90-6.32	0.114-0.249	214	31.0	262	38.0	159	23.0	. . .	. . .	9
	6.35-12.67	0.250-0.499	214	31.0	262	38.0	159	23.0	. . .	. . .	11
	12.70-50.80	0.500-2.000	214	31.0	262	38.0	159	23.0	. . .	. . .	12
5052-H34[(d)]	0.23-0.48	0.009-0.019	234	34.0	283	41.0	179	26.0	. . .	. . .	3
	0.51-1.27	0.020-0.050	234	34.0	283	41.0	179	26.0	. . .	. . .	4
	1.30-2.87	0.051-0.113	234	34.0	283	41.0	179	26.0	. . .	. . .	6
	2.90-6.32	0.114-0.249	234	34.0	283	41.0	179	26.0	. . .	. . .	7
	6.35-25.40	0.250-1.000	234	34.0	283	41.0	179	26.0	. . .	. . .	10
5052-H36[(d)]	0.15-0.18	0.006-0.007	255	37.0	303	44.0	200	29.0	. . .	. . .	2
	0.20-0.79	0.008-0.031	255	37.0	303	44.0	200	29.0	. . .	. . .	3
	0.81-4.11	0.032-0.162	255	37.0	303	44.0	200	29.0	. . .	. . .	4
5052-H38[(d)]	0.15-0.18	0.006-0.007	269	39.0	. . .	. . .	221	32.0	. . .	. . .	2
	0.20-0.79	0.008-0.031	269	39.0	. . .	. . .	221	32.0	. . .	. . .	3
	0.81-3.25	0.032-0.128	269	39.0	. . .	. . .	221	32.0	. . .	. . .	4
5052-H112	6.35-12.67	0.250-0.499	193	28.0	. . .	. . .	110	16.0	. . .	. . .	7

	12.70-05.80	0.500-2.000	172	25.0	. . .	. . .	65	9.5	. . .	. . .	12
	50.83-76.20	2.001-3.000	172	25.0	. . .	. . .	65	9.5	. . .	. . .	16
5083-O	1.30-38.10	0.051-1.500	276	40.0	352	51.0	124	18.0	200	29.0	16
	38.13-76.20	1.501-3.000	269	39.0	345	50.0	117	17.0	200	29.0	16
	76.23-101.60	3.001-4.000	262	38.0	. . .	. . .	110	16.0	. . .	. . .	16
	101.63-127.00	4.001-5.000	262	38.0	. . .	. . .	110	16.0	. . .	. . .	14
	127.03-177.80	5.001-7.000	255	37.0	. . .	. . .	103	15.0	. . .	. . .	14
	177.83-203.20	7.001-8.000	248	36.0	. . .	. . .	97	14.0	. . .	. . .	12
5083-H112	6.35-38.10	0.250-1.500	276	40.0	. . .	. . .	124	18.0	. . .	. . .	12
	38.13-76.20	1.501-3.000	269	39.0	. . .	. . .	117	17.0	. . .	. . .	12
5083-H116[(e)(f)]	0.10-12.67	0.063-0.499	303	44.0	. . .	. . .	214	31.0	. . .	. . .	10
	12.70-31.75	0.500-1.250	303	44.0	. . .	. . .	214	31.0	. . .	. . .	12
	31.78-38.10	1.251-1.500	303	44.0	. . .	. . .	214	31.0	. . .	. . .	12
	38.13-76.20	1.501-3.000	283	41.0	. . .	. . .	200	290	. . .	. . .	12
5083-H321	4.78-38.10	0.188-1.500	303	44.0	386	56.0	214	31.0	296	43.0	12
	38.13-76.20	1.501-3.000	283	41.0	386	56.0	200	29.0	296	43.0	12
5086-O	0.51-1.27	0.020-0.50	241	35.0	303	44.0	97	14.0	. . .	. . .	15
	1.30-6.32	0.051-0.249	241	35.0	303	44.0	97	14.0	. . .	. . .	18
	6.35-50.80	0.250-2.000	241	35.0	303	44.0	97	14.0	. . .	. . .	16
5086-H32[(d)]	0.51-1.27	0.020-0.050	276	40.0	324	47.0	193	28.0	. . .	. . .	6
	1.30-6.32	0.051-0.249	276	40.0	324	47.0	193	28.0	. . .	. . .	8

	6.35-50.80	0.250-2.000	276	40.0	324	47.0	193	28.0	. . .	. . .	12
5086-H34[(d)]	0.23-0.48	0.009-0.019	303	44.0	352	51.0	234	34.0	. . .	. . .	4
	0.51-1.27	0.020-0.050	303	44.0	352	51.0	234	34.0	. . .	. . .	5
	1.30-6.32	0.051-0.249	303	44.0	352	51.0	234	34.0	. . .	. . .	6
	6.35-25.40	0.250-1.000	303	44.0	352	51.0	234	34.0	. . .	. . .	10
5086-H36[(d)]	0.15-0.48	0.006-0.019	324	47.0	372	54.0	262	38.0	. . .	. . .	3
	0.51-1.27	0.020-0.050	324	47.0	372	54.0	262	38.0	. . .	. . .	4
	1.30-4.11	0.051-0.162	324	47.0	372	54.0	262	38.0	. . .	. . .	6
5086-H38[(d)]	0.15-0.51	0.006-0.020	345	50.0	. . .	. . .	283	41.0	. . .	. . .	3
5086-H112	4.78-12.67	0.188-0.499	248	36.0	. . .	. . .	124	18.0	. . .	. . .	8
	12.70-25.40	0.500-1.000	241	35.0	. . .	. . .	110	16.0	. . .	. . .	10
	25.43-50.80	1.001-2.000	241	35.0	. . .	. . .	97	14.0	. . .	. . .	14
	50.83-76.20	2.001-3.000	234	34.0	. . .	. . .	97	14.0	. . .	. . .	14
5086-H116[(e)(f)]	0.10-6.32	0.063-0.249	276	40.0	. . .	. . .	193	28.0	. . .	. . .	8
	6.35-12.67	0.250-0.499	276	40.0	. . .	. . .	193	28.0	. . .	. . .	10
	12.70-31.75	0.500-1.250	276	40.0	. . .	. . .	193	28.0	. . .	. . .	10
	31.78-50.80	1.251-2.000	276	40.0	. . .	. . .	193	28.0	. . .	. . .	10
5154-O	0.51-0.79	0.020-0.031	207	30.0	283	41.0	76	11.0	. . .	. . .	12
	0.81-1.27	0.032-0.050	207	30.0	283	41.0	76	11.0	. . .	. . .	14
	1.30-2.87	0.051-0.113	207	30.0	283	41.0	76	11.0	. . .	. . .	16
	2.90-76.20	0.114-3.000	207	30.0	283	41.0	76	11.0	. . .	. . .	18

5154-H32(d)	0.51-1.27	0.020-0.050	248	36.0	296	43.0	179	26.0	. . .	. . .	5
	1.30-6.32	0.051-0.249	248	36.0	296	43.0	179	26.0	. . .	. . .	8
	6.35-50.80	0.250-2.000	248	36.0	296	43.0	179	26.0	. . .	. . .	12
5154-H34(d)	0.23-1.27	0.009-0.050	269	39.0	317	46.0	200	29.0	. . .	. . .	4
	1.30-4.09	0.051-0.161	269	39.0	317	46.0	200	29.0	. . .	. . .	6
	4.11-6.32	0.162-0.249	269	39.0	317	46.0	200	29.0	. . .	. . .	7
	6.35-25.40	0.250-1.000	269	39.0	317	46.0	200	29.0	. . .	. . .	10
5154-H36(d)	0.15-1.27	0.006-0.050	290	42.0	338	49.0	221	32.0	. . .	. . .	3
	1.30-2.87	0.051-0.113	290	42.0	338	49.0	221	32.0	. . .	. . .	4
	2.90-4.11	0.114-0.162	290	42.0	338	49.0	221	32.0	. . .	. . .	5
5154-H38(d)	0.15-1.27	0.006-0.050	310	45.0	. . .	. . .	241	35.0	. . .	. . .	3
	1.30-2.87	0.051-0.113	310	45.0	. . .	. . .	241	35.0	. . .	. . .	4
	2.90-3.25	0.114-0.128	310	45.0	. . .	. . .	241	35.0	. . .	. . .	5
5154-H112	6.35-12.67	0.250-0.499	221	32.0	. . .	. . .	124	18.0	. . .	. . .	8
	12.70-50.80	0.500-2.000	207	30.0	. . .	. . .	76	11.0	. . .	. . .	11
	50.83-76.20	2.001-3.000	207	30.0	. . .	. . .	76	11.0	. . .	. . .	15
5454-O	0.51-0.79	0.020-0.31	214	31.0	283	41.0	83	12.0	. . .	. . .	12
	0.81-1.27	0.032-0.050	214	31.0	283	41.0	83	12.0	. . .	. . .	14
	1.30-2.87	0.051-0.113	214	31.0	283	41.0	83	12.0	. . .	. . .	16
	2.90-76.20	0.114-3.000	214	31.0	283	41.0	83	12.0	. . .	. . .	18
5454-H32(d)	0.51-1.27	0.020-0.050	248	36.0	303	44.0	179	26.0	. . .	. . .	5

	1.30-6.32	0.051-0.249	248	36.0	303	44.0	179	26.0	. . .	. . .	8
	6.35-50.80	0.250-2.000	248	36.0	303	44.0	179	26.0	. . .	. . .	12
5454-H34(d)	0.51-1.27	0.020-0.050	269	39.0	324	47.0	200	29.0	. . .	. . .	4
	1.30-4.09	0.051-0.161	269	39.0	324	47.0	200	29.0	. . .	. . .	6
	4.11-6.32	0.162-0.249	269	39.0	324	47.0	200	29.0	. . .	. . .	7
	6.35-25.40	0.250-1.000	269	39.0	324	47.0	200	29.0	. . .	. . .	10
5454-H112	6.35-12.67	0.250-0.499	221	32.0	. . .	. . .	124	18.0	. . .	. . .	8
	12.70-50.80	0.500-2.000	214	31.0	. . .	. . .	83	12.0	. . .	. . .	11
	50.83-76.20	2.001-3.000	214	31.0	. . .	. . .	83	12.0	. . .	. . .	15
5456-O	1.30-38.10	0.051-1.500	290	42.0	365	53.0	131	19.0	207	30.0	16
	38.13-76.20	1.501-3.000	283	41.0	358	52.0	124	18.0	207	30.0	16
	76.23-127.00	3.001-5.000	276	40.0	. . .	. . .	117	17.0	. . .	. . .	14
	127.03-177.80	5.001-7.000	269	39.0	. . .	. . .	110	16.0	. . .	. . .	14
	177.83-203.20	7.001-8.000	262	38.0	. . .	. . .	103	15.0	. . .	. . .	12
5456-H112(e)	6.35-38.10	0.250-1.500	290	42.0	. . .	. . .	131	19.0	. . .	. . .	12
	38.13-76.20	1.501-3.000	283	41.0	. . .	. . .	124	18.0	. . .	. . .	12
5456-H116(e)(f)	1.60-12.67	0.063-0.499	317	46.0	. . .	. . .	228	33.0	. . .	. . .	10
	12.70-31.75	0.500-1.250	317	46.0	. . .	. . .	228	33.0	. . .	. . .	12
	31.78-38.10	1.251-1.500	303	44.0	. . .	. . .	214	31.0	. . .	. . .	12
	38.13-76.20	1.501-3.000	283	41.0	. . .	. . .	200	29.0	. . .	. . .	12
	76.23-101.60	3.001-4.000	276	40.0	. . .	. . .	172	25.0	. . .	. . .	12

5456-H321	4.78-12.67	0.188-0.499	317	46.0	407	59.0	228	33.0	317	46.0	12
	12.70-38.10	0.500-1.500	303	44.0	386	56.0	214	31.0	303	44.0	12
	38.13-76.20	1.501-3.000	283	41.0	372	54.0	200	29.0	296	43.0	12
5652-O	0.15-0.18	0.006-0.007	172	25.0	214	31.0	66	9.5	. . .	. . .	. . .
	0.20-0.30	0.008-0.012	172	25.0	214	31.0	66	9.5	. . .	. . .	14
	0.33-0.48	0.013-0.019	172	25.0	214	31.0	66	9.5	. . .	. . .	15
	0.51-0.79	0.020-0.031	172	25.0	214	31.0	66	9.5	. . .	. . .	16
	0.81-1.27	0.032-0.050	172	25.0	214	31.0	66	9.5	. . .	. . .	18
	1.29-2.87	0.051-0.113	172	25.0	214	31.0	66	9.5	. . .	. . .	19
	2.90-6.32	0.114-0.249	172	25.0	214	31.0	66	9.5	. . .	. . .	20
	6.35-76.20	0.250-3.00	172	25.0	214	31.0	66	9.5	. . .	. . .	18
5652-H32(d)	0.43-0.48	0.017-0.019	214	31.0	262	38.0	159	23.0	. . .	. . .	4
	0.51-1.27	0.020-0.050	214	31.0	262	38.0	159	23.0	. . .	. . .	5
	1.29-2.87	0.051-0.113	214	31.0	262	38.0	159	23.0	. . .	. . .	7
	2.90-6.32	0.114-0.249	214	31.0	262	38.0	159	23.0	. . .	. . .	9
	6.35-12.67	0.250-0.499	214	31.0	262	38.0	159	23.0	. . .	. . .	11
	12.70-50.80	0.500-2.000	214	31.0	262	38.0	159	23.0	. . .	. . .	12
5652-H34(d)	0.23-0.48	0.009-0.019	234	34.0	283	41.0	179	26.0	. . .	. . .	3
	0.51-1.27	0.020-0.050	234	34.0	283	41.0	179	26.0	. . .	. . .	4
	1.29-2.87	0.051-0.113	234	34.0	283	41.0	179	26.0	. . .	. . .	6
	2.90-6.32	0.114-0.249	234	34.0	283	41.0	179	26.0	. . .	. . .	7

	6.35-25.4	0.250-1.000	234	34.0	283	41.0	179	26.0	. . .	. . .	10
5652-H36[(d)]	0.15-0.18	0.006-0.007	255	37.0	303	44.0	200	29.0	. . .	. . .	2
	0.20-0.79	0.008-0.031	255	37.0	303	44.0	200	29.0	. . .	. . .	3
	0.81-4.1	0.032-0.162	255	37.0	303	44.0	200	29.0	. . .	. . .	4
5652-H38[(d)]	0.15-0.18	0.006-0.007	269	39.0	. . .	. . .	221	32.0	. . .	. . .	2
	0.20-0.79	0.008-0.031	269	39.0	. . .	. . .	221	32.0	. . .	. . .	3
	0.81-3.25	0.032-0.128	269	39.0	. . .	. . .	221	32.0	. . .	. . .	4
5652-H112	6.35-12.67	0.250-0.499	193	28.0	. . .	. . .	110	16.0	. . .	. . .	7
	12.70-50.80	0.500-2.000	172	25.0	. . .	. . .	66	9.5	. . .	. . .	12
	50.83-76.20	2.001-3.000	172	25.0	. . .	. . .	66	9.5	. . .	. . .	16
5657-H241(h)	0.76-2.29	0.030-0.090	124	18.0	179	26.0	. . .	. . .	. . .	. . .	13
5657-H25	0.76-2.29	0.030-0.090	138	20.0	193	28.0	. . .	. . .	. . .	. . .	8
5657-H26	0.76-2.29	0.030-0.090	152	22.0	207	30.0	. . .	. . .	. . .	. . .	7
5657-H28	0.76-2.29	0.030-0.090	172	25.0	. . .	. . .	. . .	. . .	. . .	. . .	5

Converted SI (metric) values are for information only and are not to be used for purposes of specification, acceptance, or rejection.

(a) Type of test specimen used depends on thickness of material.

(b) Minimum yield strengths are not determined unless specifically requested.

(c) In 50 mm (2 in.) or 4*d.*

(d) For the corresponding H2 temper, limits for maximum tensile strength and minimum yield strength do not apply.

(e) When tested upon receipt by the purchaser, material in this temper is required to pass the exfoliation corrosion resistance test (ASSET method). The improved resistance to exfoliation corrosion of individual lots is determined by microscopic examination to ensure a microstructure that is predominantly free of a continuous grain-boundary network of aluminum-magnesium precipitate. The microstructure is compared with that in a previously established acceptable reference photomicrograph.

(f) Also applies to material previously designated H117.

(g) This material is subject to some recrystallization and the attendant loss of brightness.

Table 8 Mechanical-property limits for heat treatable aluminum alloy sheet and plate

Alloy and temper	Specified thickness		Tensile strength				Yield strength				Elongation (min)(a), %
			Minimum		**Maximum**		**Minimum**		**Maximum**		
	mm	**in.**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	
2014-O sheet and plate	0.51-12.67	0.020-0.499	. . .	. . .	221	32.0	. . .	. . .	110	16.0	16
	12.70-25.40	0.500-1.000	. . .	. . .	221	32.0	. . .	. . .	. . .	. . .	10
2014-T3 flat sheet	0.51-0.99	0.020-0.039	407	59.0	. . .	. . .	241	35.0	. . .	. . .	14
	1.02-6.32	0.040-0.249	407	59.0	. . .	. . .	248	36.0	. . .	. . .	14
2014-T4 coiled sheet	0.51-6.32	0.020-0.249	407	59.0	. . .	. . .	241	35.0	. . .	. . .	14
2014-T451(b)(c) plate	6.35-12.67	0.250-0.499	400	58.0	. . .	. . .	248	36.0	. . .	. . .	14
	12.70-25.40	0.500-1.000	400	58.0	. . .	. . .	248	36.0	. . .	. . .	14
	25.43-50.80	1.001-2.000	400	58.0	. . .	. . .	248	36.0	. . .	. . .	12
	50.83-76.20	2.001-3.000	393	57.0	. . .	. . .	248	36.0	. . .	. . .	8
2014-T42(d)(e) sheet and plate	0.51-25.40	0.020-1.000	400	58.0	. . .	. . .	234	34.0	. . .	. . .	14
2014-T6 and T62(d)(e) sheet	0.51-0.99	0.020-0.039	441	64.0	. . .	. . .	393	57.0	. . .	. . .	6

	1.02-6.32	0.040-0.249	441	66.0	. . .	. . .	400	58.0	. . .	. . .	7
2014-T62$^{(d)(e)}$ and T651$^{(b)}$ plate	6.35-12.67	0.250-0.499	462	67.0	. . .	. . .	407	59.0	. . .	. . .	7
	12.70-25.40	0.500-1.000	462	67.0	. . .	. . .	407	59.0	. . .	. . .	6
	25.43-50.80	1.001-2.000	462	67.0	. . .	. . .	407	59.0	. . .	. . .	4
	50.83-63.50	2.001-2.500	448	65.0	. . .	. . .	400	58.0	. . .	. . .	2
	63.53-76.20	2.501-3.000	434	63.0	. . .	. . .	393	57.0	. . .	. . .	2
	76.23-101.60	3.001-4.000	407	59.0	. . .	. . .	379	55.0	. . .	. . .	1
2024-O sheet and plate	0.25-12.67	0.010-0.499	. . .	. . .	221	32.0	. . .	. . .	97	14.0	12
	12.70-44.45	0.500-1.750	. . .	. . .	221	32.0	. . .	. . .	. . .	. . .	12
2024-T3$^{(c)}$ flat sheet	0.20-0.23	0.008-0.009	434	63.0	. . .	. . .	290	42.0	. . .	. . .	10
	0.25-0.51	0.010-0.020	434	63.0	. . .	. . .	290	42.0	. . .	. . .	12
	0.53-3.25	0.021-0.18	434	63.0	. . .	. . .	290	42.0	. . .	. . .	15
	3.28-6.32	0.129-0.249	441	64.0	. . .	. . .	290	42.0	. . .	. . .	15
2024-T361$^{(c)(f)}$ flat sheet and plate	0.51-1.57	0.020-0.062	462	67.0	. . .	. . .	345	50.0	. . .	. . .	8
	1.60-6.32	0.063-0.249	469	68.0	. . .	. . .	352	51.0	. . .	. . .	9
	6.35-12.67	0.250-0.499	455	66.0	. . .	. . .	338	49.0	. . .	. . .	9

	12.70	0.500	455	66.0	. . .	. . .	338	49.0	. . .	. . .	10
2024-T4 coiled sheet	0.25-0.51	0.010-0.020	427	62.0	. . .	. . .	276	40.0	. . .	. . .	12
	0.53-6.32	0.021-0.249	427	62.0	. . .	. . .	276	40.0	. . .	. . .	15
2024-T351(b)(c) plate	6.35-12.67	0.250-0.499	441	64.0	. . .	. . .	290	42.0	. . .	. . .	12
	12.70-25.40	0.500-1.000	434	63.0	. . .	. . .	290	42.0	. . .	. . .	8
	25.43-38.10	1.001-1.500	427	62.0	. . .	. . .	290	42.0	. . .	. . .	7
	38.13-50.80	1.501-2.000	427	62.0	. . .	. . .	290	42.0	. . .	. . .	6
	50.83-76.20	2.001-3.000	414	60.0	. . .	. . .	290	42.0	. . .	. . .	4
	76.23-101.60	3.001-4.000	393	57.0	. . .	. . .	283	41.0	. . .	. . .	4
2024-T42(d)(e) sheet and plate	0.25-0.51	0.010-0.020	427	62.0	. . .	. . .	262	38.0	. . .	. . .	12
	0.53-6.32	0.021-0.249	427	62.0	. . .	. . .	262	38.0	. . .	. . .	15
	6.35-12.67	0.250-0.499	427	62.0	. . .	. . .	262	38.0	. . .	. . .	12
	12.70-25.40	0.500-1.000	421	61.0	. . .	. . .	262	38.0	. . .	. . .	8
	25.43-38.10	1.001-1.500	414	60.0	. . .	. . .	262	38.0	. . .	. . .	7
	38.13-50.80	1.501-2.000	414	60.0	. . .	. . .	262	38.0	. . .	. . .	6
	50.83-76.20	2.001-3.000	400	58.0	. . .	. . .	262	38.0	. . .	. . .	4

2219-T62$^{(d)(e)}$ sheet and plate	0.51-0.99	0.020-0.039	372	54.0	. . .	. . .	248	36.0	. . .	. . .	6
	1.02-6.32	0.040-0.249	372	54.0	. . .	. . .	248	36.0	. . .	. . .	7
	6.35-25.40	0.250-1.000	372	54.0	. . .	. . .	248	36.0	. . .	. . .	8
	25.43-50.80	1.001-2.000	372	54.0	. . .	. . .	248	36.0	. . .	. . .	7
2219-T81 flat sheet	0.51-0.99	0.020-0.039	427	62.0	. . .	. . .	317	46.0	. . .	. . .	6
	1.02-6.32	0.040-0.249	427	62.0	. . .	. . .	317	46.0	. . .	. . .	7
2219-T851$^{(b)}$ plate	6.35-25.40	0.250-1.000	427	62.0	. . .	. . .	317	46.0	. . .	. . .	8
	25.43-50.80	1.001-2.000	427	62.0	. . .	. . .	317	46.0	. . .	. . .	7
	50.83-76.20	2.001-3.000	427	62.0	. . .	. . .	310	45.0	. . .	. . .	6
	76.23-101.60	3.001-4.000	414	60.0	. . .	. . .	303	44.0	. . .	. . .	5
	101.63-127.00	4.001-5.000	407	59.0	. . .	. . .	296	43.0	. . .	. . .	5
	127.03-152.40	5.001-6.000	393	57.0	. . .	. . .	290	42.0	. . .	. . .	4
2219-T87 flat sheet and plate	0.51-0.99	0.020-0.039	441	64.0	. . .	. . .	358	52.0	. . .	. . .	5
	1.02-6.32	0.040-0.249	441	64.0	. . .	. . .	358	52.0	. . .	. . .	6
	6.35-25.40	0.250-1.000	441	64.0	. . .	. . .	352	51.0	. . .	. . .	7
	25.43-50.80	1.001-2.000	441	64.0	. . .	. . .	352	51.0	. . .	. . .	6

	50.83-76.20	2.001-3.000	441	64.0	. . .	. . .	352	51.0	. . .	. . .	6
	76.23-101.60	3.001-4.000	427	62.0	. . .	. . .	345	50.0	. . .	. . .	4
	101.63-127.00	4.001-5.000	421	61.0	. . .	. . .	338	49.0	. . .	. . .	3
6061-O sheet and plate	0.15-0.18	0.006-0.007	. . .	. . .	152	22.0	. . .	. . .	83	12.0	10
	0.20-0.23	0.008-0.009	. . .	. . .	152	22.0	. . .	. . .	83	12.0	12
	0.25-0.51	0.010-0.020	. . .	. . .	152	22.0	. . .	. . .	83	12.0	14
	0.53-3.25	0.021-0.128	. . .	. . .	152	22.0	. . .	. . .	83	12.0	16
	3.28-12.67	0.129-0.499	. . .	. . .	152	22.0	. . .	. . .	83	12.0	18
	12.70-25.40	0.500-1.000	. . .	. . .	152	22.0	. . .	. . .	. . .	. . .	18
	25.43-76.20	1.001-3.000	. . .	. . .	152	22.0	. . .	. . .	. . .	. . .	16
6061-T4 sheet	0.15-0.18	0.006-0.007	207	30.0	. . .	. . .	110	16.0	. . .	. . .	10
	0.20-0.23	0.008-0.009	207	30.0	. . .	. . .	110	16.0	. . .	. . .	12
	0.25-0.51	0.010-0.020	207	30.0	. . .	. . .	110	16.0	. . .	. . .	14
	0.53-6.32	0.021-0.249	207	30.0	. . .	. . .	110	16.0	. . .	. . .	16
6061-T451[(b)(c)] plate	6.35-25.40	0.250-1.000	207	30.0	. . .	. . .	110	16.0	. . .	. . .	18
	25.43-76.20	1.001-3.000	207	30.0	. . .	. . .	110	16.0	. . .	. . .	16

6061-T42(d)(e) sheet and plate	0.15-0.18	0.006-0.007	207	30.0	. . .	. . .	97	14.0	. . .	. . .	10
	0.20-0.23	0.008-0.009	207	30.0	. . .	. . .	97	14.0	. . .	. . .	12
	0.25-0.51	0.010-0.020	207	30.0	. . .	. . .	97	14.0	. . .	. . .	14
	0.53-6.32	0.021-0.249	207	30.0	. . .	. . .	97	14.0	. . .	. . .	16
	6.35-25.40	0.250-1.000	207	30.0	. . .	. . .	97	14.0	. . .	. . .	18
	25.43-76.20	1.001-3.000	207	30.0	. . .	. . .	97	14.0	. . .	. . .	16
6061-T6 and T62(d)(e) sheet	0.15-0.18	0.006-0.007	290	42.0	. . .	. . .	241	35.0	. . .	. . .	4
	0.20-0.23	0.008-0.009	290	42.0	. . .	. . .	241	35.0	. . .	. . .	6
	0.25-0.51	0.010-0.020	290	42.0	. . .	. . .	241	35.0	. . .	. . .	8
	0.53-6.32	0.021-0.249	290	42.0	. . .	. . .	241	35.0	. . .	. . .	10
6061-T62(d)(e) and T651(b) plate	6.35-12.67	0.250-0.499	290	42.0	. . .	. . .	241	35.0	. . .	. . .	10
	12.70-25.40	0.500-1.000	290	42.0	. . .	. . .	241	35.0	. . .	. . .	9
	25.43-50.80	1.001-2.000	290	42.0	. . .	. . .	241	35.0	. . .	. . .	8
	50.83-101.60	2.001-4.000	290	42.0	. . .	. . .	241	35.0	. . .	. . .	6
	101.63-152.40	4.001-6.00(h)	276	40.0	. . .	. . .	241	35.0	. . .	. . .	6
7075-O sheet and plate	0.38-12.67	0.015-0.499	. . .	. . .	276	40.0	. . .	. . .	145	21.0	10

	12.70-50.80	0.500-2.000	. . .	. . .	276	40.0	. . .	. . .	. . .	. . .	10
7075-T6 and T62(d)(e) sheet	0.20-0.28	0.008-0.011	510	74.0	. . .	. . .	434	63.0	. . .	. . .	5
	0.30-0.99	0.012-0.039	524	76.0	. . .	. . .	462	67.0	. . .	. . .	7
	1.02-3.18	0.040-0.125	538	78.0	. . .	. . .	469	68.0	. . .	. . .	8
	3.21-6.32	0.126-0.249	538	78.0	. . .	. . .	476	69.0	. . .	. . .	8
7075-T62(d)(e) and T651(b) plate	6.35-12.67	0.250-0.499	538	78.0	. . .	. . .	462	67.0	. . .	. . .	9
	12.70-25.40	0.500-1.000	538	78.0	. . .	. . .	469	68.0	. . .	. . .	7
	25.43-50.80	1.001-2.000	531	77.0	. . .	. . .	462	67.0	. . .	. . .	6
	50.83-63.50	2.001-2.500	524	76.0	. . .	. . .	441	64.0	. . .	. . .	5
	63.53-76.20	2.501-3.000	496	72.0	. . .	. . .	421	61.0	. . .	. . .	5
	76.23-88.90	3.001-3.500	489	71.0	. . .	. . .	400	58.0	. . .	. . .	5
	88.93-101.60	3.501-4.000	462	67.0	. . .	. . .	372	54.0	. . .	. . .	3
7075-T73(i) sheet	1.02-6.32	0.040-0.249	462	67.0	. . .	. . .	386	56.0	. . .	. . .	8
7075-T7351(b)(i) plate	6.35-25.40	0.250-1.000	476	69.0	. . .	. . .	393	57.0	. . .	. . .	7
	25.43-50.80	1.001-2.000	476	69.0	. . .	. . .	393	57.0	. . .	. . .	6
	50.83-63.50	2.001-2.500	455	66.0	. . .	. . .	358	52.0	. . .	. . .	6

	63.53-76.20	2.501-3.000	441	64.0	. . .	. . .	338	49.0	. . .	. . .	6
7075-T76[j] sheet	3.18-6.32	0.125-0.249	503	73.0	. . .	. . .	427	62.0	. . .	. . .	8
7075-T7351[b][i] plate	6.35-25.40	0.250-1.000	476	69.0	. . .	. . .	393	57.0	. . .	. . .	7
	25.43-50.80	1.001-2.000	476	69.0	. . .	. . .	393	57.0	. . .	. . .	6
	50.83-63.50	2.001-2.500	455	66.0	. . .	. . .	358	52.0	. . .	. . .	6
	63.53-76.20	2.501-3.000	441	64.0	. . .	. . .	338	49.0	. . .	. . .	6
7075-T76[j] sheet	3.18-6.32	0.125-0.249	503	73.0	. . .	. . .	427	62.0	. . .	. . .	8
7075-T7651[d][j] plate	6.35-12.67	0.250-0.499	496	72.0	. . .	. . .	421	61.0	. . .	. . .	8
	12.70-25.40	0.500-1.000	489	71.0	. . .	. . .	414	60.0	. . .	. . .	6
7178-O sheet and plate	0.38-12.67	0.015-0.499	. . .	. . .	276	40.0	. . .	. . .	145	21.0	10
	12.70	0.500	. . .	. . .	276	40.0	. . .	. . .	. . .	. . .	10
7178-T6 and T62[d][e] sheet	0.38-1.12	0.015-0.044	572	83.0	. . .	. . .	496	72.0	. . .	. . .	7
	1.14-6.32	0.045-0.249	579	84.0	. . .	. . .	503	73.0	. . .	. . .	8
7178-T62[d][e] and T651[b] plate	6.35-12.67	0.250-0.499	579	84.0	. . .	. . .	503	73.0	. . .	. . .	8
	12.70-25.40	0.500-1.000	579	84.0	. . .	. . .	503	73.0	. . .	. . .	6
	25.43-38.10	1.001-1.500	579	84.0	. . .	. . .	503	73.0	. . .	. . .	4

	38.13-50.80	1.501-2.000	552	80.0	. . .	. . .	483	70.0	. . .	. . .	3
2024-T62(d)(e) sheet and plate	0.25-12.67	0.010-0.499	441	64.0	. . .	. . .	345	50.0	. . .	. . .	5
	12.70-76.20	0.500-3.000	434	63.0	. . .	. . .	345	50.0	. . .	. . .	5
2024-T72(d)(e) sheet	0.25-6.32	0.010-0.249	414	60.0	. . .	. . .	317	46.0	. . .	. . .	5
2024-T81 flat sheet	0.25-6.32	0.010-0.249	462	67.0	. . .	. . .	400	58.0	. . .	. . .	5
2024-T851(b) plate	6.35-12.67	0.250-0.499	462	67.0	. . .	. . .	400	58.0	. . .	. . .	5
	12.70-25.40	0.500-1.000	455	66.0	. . .	. . .	400	58.0	. . .	. . .	5
	25.43-38.07	1.001-1.499	455	66.0	. . .	. . .	393	57.0	. . .	. . .	5
2024-T861(f) flat sheet and plate	0.51-1.57	0.020-0.062	483	70.0	. . .	. . .	427	62.0	. . .	. . .	3
	1.60-6.32	0.063-0.249	489	71.0	. . .	. . .	455	66.0	. . .	. . .	4
	6.35-12.67	0.250-0.499	483	70.0	. . .	. . .	441	64.0	. . .	. . .	4
	12.70	0.500	483	70.0	. . .	. . .	441	64.0	. . .	. . .	4
Alclad 2024-O sheet and plate	0.20-0.23	0.008-0.009	. . .	. . .	207	30.0	. . .	. . .	97	14.0	10
	0.25-0.81	0.010-0.032	. . .	. . .	207	30.0	. . .	. . .	97	14.0	12
	0.84-1.57	0.033-0062	. . .	. . .	207	30.0	. . .	. . .	97	14.0	12
	1.60-4.75	0.063-0.187	. . .	. . .	221	32.0	. . .	. . .	97	14.0	12

	4.78-12.67	0.188-0.499	. . .	. . .	221	32.0	. . .	. . .	97	14.0	12
	12.70-44.45	0.500-1.750	. . .	. . .	221	32.0[h]	. . .	. . .	. . .	. . .	12
Alclad 2024-T3[c] flat sheet	0.20-0.23	0.008-0.009	400	58.0	. . .	. . .	269	39.0	. . .	. . .	10
	0.25-0.51	0.010-0.020	407	59.0	. . .	. . .	269	39.0	. . .	. . .	12
	0.53-1.57	0.021-0.062	407	59.0	. . .	. . .	269	39.0	. . .	. . .	15
	1.60-3.25	0.063-0.128	421	61.0	. . .	. . .	276	40.0	. . .	. . .	15
	3.28-6.32	0.129-0.249	427	62.0	. . .	. . .	276	40.0	. . .	. . .	15
Alclad 2024-T361[c][f] flat sheet and plate	0.51-1.57	0.020-0.062	421	61.0	. . .	. . .	324	47.0	. . .	. . .	8
	1.60-4.75	0.063-0.187	441	64.0	. . .	. . .	331	48.0	. . .	. . .	9
	4.78-6.32	0.188-0.249	441	64.0	. . .	. . .	331	48.0	. . .	. . .	9
	6.35-12.67	0.250-0.499	441	64.0	. . .	. . .	331	48.0	. . .	. . .	9
	12.70	0.500	455	66.0[g]	. . .	. . .	338	49.0[g]	. . .	. . .	10
Alclad 2024-T4 coiled sheet	0.25-0.51	0.010-0.020	400	58.0	. . .	. . .	248	36.0	. . .	. . .	12
	0.53-1.57	0.021-0.062	400	58.0	. . .	. . .	248	36.0	. . .	. . .	15
	1.60-3.25	0.063-0.128	421	61.0	. . .	. . .	262	38.0	. . .	. . .	15
Alclad 2024-T351[b][c] plate	6.35-12.67	0.250-0.499	427	62.0	. . .	. . .	276	40.0	. . .	. . .	12

	12.70-25.40	0.500-1.000	434	63.0(g)	. . .	. . .	290	42.0(g)	. . .	. . .	8
	25.43-38.10	1.001-1.500	427	62.0(g)	. . .	. . .	290	42.0(g)	. . .	. . .	7
	38.13-50.80	1.501-2.000	427	62.0(g)	. . .	. . .	290	42.0(g)	. . .	. . .	6
	50.83-76.20	2.001-3.000	414	60.0(g)	. . .	. . .	290	42.0(g)	. . .	. . .	4
	76.23-101.60	3.001-4.000	393	57.0(g)	. . .	. . .	283	41.0(g)	. . .	. . .	4
Alclad 2024-T42(d)(e) sheet and plate	0.20-0.23	0.008-0.009	379	55.0	. . .	. . .	234	34.0	. . .	. . .	10
	0.25-0.51	0.010-0.020	393	57.0	. . .	. . .	234	34.0	. . .	. . .	12
	0.53-1.57	0.021-0.062	393	57.0	. . .	. . .	234	34.0	. . .	. . .	15
	1.60-4.75	0.063-0.187	414	60.0	. . .	. . .	248	36.0	. . .	. . .	15
	4.78-6.32	0.188-0.249	414	60.0	. . .	. . .	248	36.0	. . .	. . .	15
	6.35-12.67	0.250-0.499	414	60.0	. . .	. . .	248	36.0	. . .	. . .	12
	12.70-25.40	0.500-1.000	421	61.0(g)	. . .	. . .	262	38.0(g)	. . .	. . .	8
	25.43-38.10	1.001-1.500	414	60.0(g)	. . .	. . .	262	38.0(g)	. . .	. . .	7
	38.13-50.80	1.501-2.000	414	60.0(g)	. . .	. . .	262	38.0(g)	. . .	. . .	6
	50.83-76.20	2.001-3.000	400	58.0(g)	. . .	. . .	262	38.0(g)	. . .	. . .	4
Alclad 2024-T62(d)(e) sheet and plate	0.25-1.57	0.010-0.062	414	60.0	. . .	. . .	324	47.0	. . .	. . .	5

	1.60-4.75	0.063-0.187	427	62.0	. . .	. . .	338	49.0	. . .	. . .	5
	4.78-12.67	0.188-0.499	427	62.0	. . .	. . .	338	49.0	. . .	. . .	5
Alclad 2024-T72[d][e] sheet	0.25-1.57	0.010-0.062	386	56.0	. . .	. . .	296	43.0	. . .	. . .	5
	1.60-4.75	0.063-0.187	400	58.0	. . .	. . .	310	45.0	. . .	. . .	5
	4.78-6.32	0.188-0.249	400	58.0	. . .	. . .	310	45.0	. . .	. . .	5
Alclad 2024-T81 flat sheet	0.25-1.57	0.010-0.062	427	62.0	. . .	. . .	372	54.0	. . .	. . .	5
	1.60-4.75	0.063-0.187	448	65.0	. . .	. . .	386	56.0	. . .	. . .	5
	4.78-6.32	0.188-0.249	448	65.0	. . .	. . .	386	56.0	. . .	. . .	5
Alclad 2024-T851[b] plate	6.35-12.67	0.250-0.499	488	65.0	. . .	. . .	386	56.0	. . .	. . .	5
	12.70-25.40	0.500-1.000	455	66.0[g]	. . .	. . .	400	58.0[g]	. . .	. . .	5
Alclad 2024-T861[f] flat sheet and plate	0.51-1.57	0.020-0.062	441	64.0	. . .	. . .	400	58.0	. . .	. . .	3
	1.60-4.75	0.063-0.187	476	69.0	. . .	. . .	441	64.0	. . .	. . .	4
	4.78-6.32	0.188-0.249	476	69.0	. . .	. . .	441	64.0	. . .	. . .	4
	6.35-12.67	0.250-0.499	469	68.0	. . .	. . .	427	62.0	. . .	. . .	4
	12.70	0.500	483	70.0[g]	. . .	. . .	441	64.0	. . .	. . .	4
2036-T4 flat sheet	0.64-3.18	0.025-0.125	290	42.0	. . .	. . .	159	23.0	. . .	. . .	20

2219-O sheet and plate	0.51-50.83	0.020-2.000	. . .	. . .	221	32.0	. . .	. . .	110	16.0	12
2219-T31[(c)] flat sheet	0.51-0.99	0.020-0.039	317	46.0	. . .	. . .	200	29.0	. . .	. . .	8
	1.02-6.32	0.040-0.249	317	46.0	. . .	. . .	193	28.0	. . .	. . .	10
2219-T351[(b)(c)] plate	6.35-50.80	0.250-2.000	317	46.0	. . .	. . .	193	28.0	. . .	. . .	10
	50.83-76.20	2.001-3.000	303	44.0	. . .	. . .	193	28.0	. . .	. . .	10
	76.23-101.60	3.001-4.000	290	42.0	. . .	. . .	186	27.0	. . .	. . .	9
	101.63-127.00	4.001-5.000	276	40.0	. . .	. . .	179	26.0	. . .	. . .	9
	127.03-152.40	5.001-6.000	269	39.0	. . .	. . .	172	25.0	. . .	. . .	8
2219-T37[(c)] flat sheet and plate	0.51-0.99	0.020-0.039	338	49.0	. . .	. . .	262	38.0	. . .	. . .	6
	1.02-50.80	0.040-2.000	338	49.0	. . .	. . .	255	37.0	. . .	. . .	6
	50.83-63.50	2.01-2.500	338	49.0	. . .	. . .	255	37.0	. . .	. . .	6
	63.53-76.20	2.501-3.000	324	47.0	. . .	. . .	248	36.0	. . .	. . .	6
	76.23-101.60	3.001-4.000	310	45.0	. . .	. . .	241	35.0	. . .	. . .	5
	101.63-127.00	4.001-5.000	296	43.0	. . .	. . .	234	34.0	. . .	. . .	4
7178-T76[(j)] sheet	1.14-6.32	0.045-0.249	517	75.0	. . .	. . .	441	64.0	. . .	. . .	8
7178-T7651[(b)(j)] plate	6.35-12.67	0.250-0.499	510	74.0	. . .	. . .	434	63.0	. . .	. . .	8

	12.70-25.40	0.500-1.000	503	73.0	. . .	. . .	427	62.0	. . .	. . .	6
7475-T61 sheet	1.02-6.32	0.040-0.249	490	71.0	. . .	. . .	414	60.0	. . .	. . .	9

Alloy and temper	Specified thickness		Axis of test specimen[k]	Tensile strength				Yield strength				Elongation (min)[a], %
				Minimum		**Maximum**		**Minimum**		**Maximum**		
	mm	**in.**		**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	
2124-T851[b] plate	38.10-50.80	1.500-2.000	L	455	66.0	. . .	. . .	393	57.0	. . .	. . .	6
			LT	455	66.0	. . .	. . .	393	57.0	. . .	. . .	5
			ST	441	64.0	. . .	. . .	379	55.0	. . .	. . .	1.5
	50.83-76.20	2.001-3.000	L	448	65.0	. . .	. . .	393	57.0	. . .	. . .	6
			LT	448	65.0	. . .	. . .	393	57.0	. . .	. . .	4
			ST	434	63.0	. . .	. . .	379	55.0	. . .	. . .	1.5
	76.23-101.60	3.001-4.000	L	448	65.0	. . .	. . .	386	56.0	. . .	. . .	5
			LT	448	65.0	. . .	. . .	386	56.0	. . .	. . .	4
			ST	427	62.0	. . .	. . .	372	54.0	. . .	. . .	1.5
	101.63-127.00	4.001-5.000	L	441	64.0	. . .	. . .	379	55.0	. . .	. . .	5
			LT	441	64.0	. . .	. . .	379	55.0	. . .	. . .	4
			ST	421	61.0	. . .	. . .	365	53.0	. . .	. . .	1.5
	127.03-152.40	5.001-6.000	L	434	63.0	. . .	. . .	372	54.0	. . .	. . .	5
			LT	434	63.0	. . .	. . .	372	54.0	. . .	. . .	4
			ST	400	58.0	. . .	. . .	352	51.0	. . .	. . .	1.5

7050-T7451(b)(i) (formerly 7050-T73651) plate	6.35-50.80	0.250-2.000	L	510	74.0	. . .	. . .	441	64.0	. . .	. . .	10
			LT	510	74.0	. . .	. . .	441	64.0	. . .	. . .	9
			ST	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	50.83-76.20	2.001-3.000	L	503	73.0	. . .	. . .	434	63.0	. . .	. . .	9
			LT	503	73.0	. . .	. . .	434	63.0	. . .	. . .	8
			ST	469	68.0	. . .	. . .	407	59.0	. . .	. . .	2
	76.23-101.60	3.001-4.000	L	496	72.0	. . .	. . .	427	62.0	. . .	. . .	9
			LT	496	72.0	. . .	. . .	427	62.0	. . .	. . .	6
			ST	469	68.0	. . .	. . .	400	58.0	. . .	. . .	2
	101.63-127.00	4.001-5.000	L	489	71.0	. . .	. . .	421	61.0	. . .	. . .	9
			LT	489	71.0	. . .	. . .	421	61.0	. . .	. . .	5
			ST	462	67.0	. . .	. . .	393	57.0	. . .	. . .	2
	127.03-152.40	5.001-6.000	L	483	70.0	. . .	. . .	414	60.0	. . .	. . .	8
			LT	483	70.0	. . .	. . .	414	60.0	. . .	. . .	4
			ST	462	67.0	. . .	. . .	393	57.0	. . .	. . .	2
7050-T7651(b)(j) plate	6.35-25.40	0.250-1.000	L	524	76.0	. . .	. . .	455	66.0	. . .	. . .	9
			LT	524	76.0	. . .	. . .	455	66.0	. . .	. . .	8
			ST	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	25.43-38.10	1.001-1.500	L	531	77.0	. . .	. . .	462	67.0	. . .	. . .	9
			LT	531	77.0	. . .	. . .	462	67.0	. . .	. . .	8
			ST	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

	38.13- 50.80	1.501- 2.000	L	524	76.0	...	...	455	66.0	...	...	9
			LT	524	76.0	...	...	455	66.0	...	...	8
			ST	...	...	...	...	...	...	...	...	...
	50.83- 76.20	2.001- 3.000	L	524	76.0	...	...	455	66.0	...	...	8
			LT	524	76.0	...	...	455	66.0	...	...	7
			ST	...	...	...	...	...	...	...	...	1.5
7475-T7351 plate	6.35- 38.10	0.250- 1.500	L	490	71.0	...	...	414	60.0	...	...	10
			LT	490	71.0	...	...	414	60.0	...	...	9
	25.43- 38.10	1.001- 1.500	ST	462(1)	67.0(1)	...	...	386(1)	56.0(1)	...	...	4(1)
	38.12- 50.80	1.501- 2.000	L	483	70.0	...	...	400	58.0	...	...	10
			LT	483	70.0	...	...	400	58.0	...	...	8
			ST	455	66.0	...	...	372	54.0	...	...	4
	50.83- 63.50	2.001- 2.500	L	476	69.0	...	...	393	57.0	...	...	10
			LT	476	69.0	...	...	393	57.0	...	...	8
			ST	448	65.0	...	...	365	53.0	...	...	4
	63.53- 76.20	2.501- 3.000	L	469	68.0	...	...	386	56.0	...	...	10
			LT	469	68.0	...	...	386	56.0	...	...	8
			ST	448	65.0	...	...	365	53.0	...	...	3
	76.23- 88.90	3.001- 3.500	L	448	65.0	...	...	365	53.0	...	...	10
			LT	448	65.0	...	...	365	53.0	...	...	8

			ST	448	65.0	. . .	. . .	352	51.0	. . .	. . .	3
	88.93-101.60	3.501-4.000	L	441	64.0	. . .	. . .	359	52.0	. . .	. . .	9
			LT	441	64.0	. . .	. . .	359	52.0	. . .	. . .	7
			ST	434	63.0	. . .	. . .	345	50.0	. . .	. . .	3

Converted SI (metric) values are for information only and are not to be used for purposes of specification, acceptance, or rejection.

(a) In 50 mm (2 in.) or 4*d.*

(b) For stress-relieved tempers, the characteristics and properties other than those specified may differ somewhat from the corresponding characteristics and properties of material in the basic temper.

(c) Upon artificial aging, material in the T3/T31, T37, T351, T36, and T451 tempers is capable of developing the mechanical properties applicable to material in the T81, T87, T851, T861 and T651 tempers, respectively.

(d) These properties usually can be obtained by the user when the material is properly solution heat treated or solution and precipitation heat treated from the O (annealed) or F (as fabricated) temper. These properties also apply to samples of material in the O and F tempers, which are solution heat treated or solution and precipitation heat treated by the producer to determine that the material will respond to proper heat treatment. Properties attained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

(e) This temper is not available from the material producer.

(f) Tempers T361 and T861 were formerly designated T36 and T86, respectively.

(g) This table specifies properties applicable to test specimens, and, because for plate in thicknesses of 0.500 in. or greater the cladding material is removed during preparation of specimens, the listed properties are applicable to the core material only. Tensile and yield strengths of the composite plate are slightly lower depending on cladding thickness.

(h) The properties given for this thickness apply only to the T651 temper.

(i) When subjected to stress-corrosion testing, material in this temper is capable of exhibiting no evidence of stress-corrosion cracking when exposed for a period of 30 days in the short-transverse direction at a stress level of 75% of the specified yield strength. The stress-corrosion resistance capabilities of individual lots are determined by testing the previously selected tensile-test specimens in accordance with the applicable electrical conductivity acceptance criteria.

(j) Material in this temper, when tested upon receipt by the purchaser, is capable of passing an exfoliation corrosion resistance test and the stress-corrosion criteria of some tests except that the stress level should be 25.0 ksi. The improved resistance to exfoliation corrosion and stress-corrosion cracking of individual lots is determined by testing the previously selected tensile-test specimens in accordance with the applicable electrical conductivity acceptance criteria

(k) L, longitudinal; LT, long transverse; ST, short transverse

(l) Applies to 38.10 mm (1.500 in.) thickness only

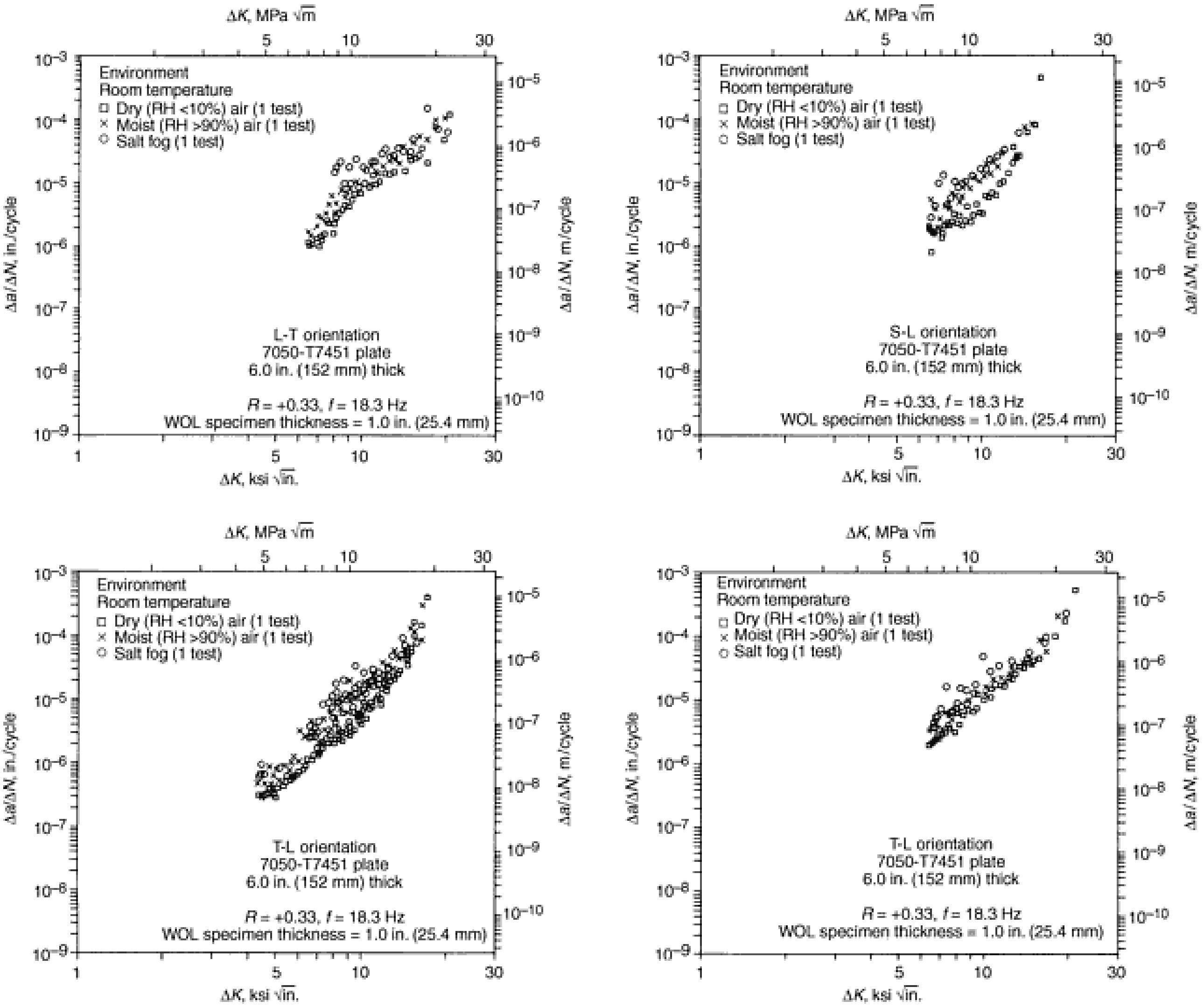


Fig. 4 Fatigue-crack-growth rates as functions of stress-intensity factor for two thicknesses of 7050-T7451 plate tested in three directions and in three environments

Table 9 Mechanical property limits for non-heat-treatable aluminum alloy extruded wire, rod, bar, and shapes

Alloy and temper	Specified diameter or thickness(a)		Area		Tensile strength				Yield strength (min)		Elongation (min)(b), %
					Minimum		**Maximum**				
	mm	**in.**	**cm^2**	**in.^{2}**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	
1100-O	All	All	All	All	76	11.0	107	15.5	21	3.0	25
1100-H112	All	All	All	All	76	11.0	. . .	. . .	21	3.0	. . .

3003-O	All	All	All	All	97	14.0	131	19.0	34	5.0	25
3003-H112	All	All	All	All	97	14.0	. . .	. . .	34	5.0	. . .
5083-O	≤127	≤5.000	≤206	≤32	269	39.0	352	51.0	110	16.0	14
5083-H111	≤127	≤5.000	≤206	≤32	276	40.0	. . .	. . .	165	24.0	12
5083-H112	≤127	≤5.000	≤206	≤32	269	39.0	. . .	. . .	110	16.0	12
5086-O	≤127	≤5.000	≤206	≤32	241	35.0	317	46.0	97	14.0	14
5086-H111	≤127	≤5.000	≤206	≤32	248	36.0	. . .	. . .	145	21.0	12
5086-H112	≤127	≤5.000	≤206	≤32	241	35.0	. . .	. . .	97	14.0	12
5154-O	All	All	All	All	207	30.0	283	41.0	76	11.0	. . .
5154-H112	All	All	All	All	207	30.0	. . .	. . .	76	11.0	. . .
5454-O	≤127	≤5.000	≤206	≤32	214	31.0	283	41.0	83	12.0	14
5454-H111	≤127	≤5.000	≤206	≤32	228	33.0	. . .	. . .	131	19.0	12
5454-H112	≤127	≤5.000	≤206	≤32	214	31.0	. . .	. . .	83	12.0	12

Converted SI (metric) values are for information only and are not to be used for purposes of specification, acceptance, or rejection.

(a) The thickness of the cross section from which the tensile-test specimen is taken determines the applicable mechanical properties.

(b) In 50 mm (2 in.) or 4*d.*

Table 10 Mechanical-property limits for heat-treatable aluminum alloy extruded wire, rod, bar, and shapes

Alloy and temper	Specified diameter or thickness(a)		Area		Tensile strength				Yield strength				Elongation (min)(b), %
					Minimum		**Maximum**		**Minimum**		**Maximum**		
	mm	**in.**	**cm^2**	**$in.^2$**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	

2014-O	All	All	All	All	. . .	. . .	207	30.0	. . .	. . .	124	18.0	12
2014-T4, T4510[(c)(d)] and T4511[(c)(d)]	All	All	All	All	345	50.0	. . .	. . .	241	35.0	. . .	. . .	12
2014-T42[(e)(f)]	All	All	All	All	345	50.0	. . .	. . .	200	29.0	. . .	. . .	12
2014-T6, T6510[(c)] and T6511[(c)]	≤12.67	≤ 0.499	All	All	414	60.0	. . .	. . .	365	53.0	. . .	. . .	7
	12.70-19.02	0.500-0.749	All	All	441	64.0	. . .	. . .	400	58.0	. . .	. . .	7
	≥19.05	≥0.750	≤161	≤ 25	469	68.0	. . .	. . .	414	60.0	. . .	. . .	7
	≥19.05	≥0.750	>161-206	>25-32	469	68.0	. . .	. . .	400	58.0	. . .	. . .	6
2014-T62[(e)(f)]	≤19.02	≤ 0.749	All	All	414	60.0	. . .	. . .	365	53.0	. . .	. . .	7
	≥19.05	≥0.750	≤161	≤ 25	414	60.0	. . .	. . .	365	53.0	. . .	. . .	7
	≥19.05	≥0.750	>161-206	>25-32	414	60.0	. . .	. . .	365	53.0	. . .	. . .	6
2024-O	All	All	All	All	. . .	. . .	241	35.0	. . .	. . .	131	19.0	12
2024-T3, T3510[(c)(d)] T3511[(c)(d)]	≤6.32	≤ 0.249	All	All	393	57.0	. . .	. . .	290	42.0	. . .	. . .	12
	6.35-19.02	0.250-0.749	All	All	414	60.0	. . .	. . .	303	44.0	. . .	. . .	12
	19.05-38.07	0.750-1.499	All	All	448	65.0	. . .	. . .	317	46.0	. . .	. . .	10
	≥38.10	≥1.500	≤161	≤ 25	483	70.0	. . .	. . .	358	52.0	. . .	. . .	10
	≥38.10	≥1.500	>161-206	>25-32	469	68.0	. . .	. . .	331	48.0	. . .	. . .	8

2024-T42[e][f]	≤19.02	≤ 0.749	All	All	393	57.0	. . .	. . .	262	38.0	. . .	. . .	12
	19.05-38.07	0.750-1.499	All	All	393	57.0	. . .	. . .	262	38.0	. . .	. . .	10
	≥38.10	≥1.500	≤161	≤ 25	393	57.0	. . .	. . .	262	38.0	. . .	. . .	10
	≥38.10	≥1.500	>161-206	>25-32	393	57.0	. . .	. . .	262	38.0	. . .	. . .	8
2024-T81, T8510[c]and T8511[c]	1.27-6.32	0.050-0.249	All	All	441	64.0	. . .	. . .	386	56.0	. . .	. . .	4
	6.35-38.07	0.250-1.499	All	All	455	66.0	. . .	. . .	400	58.0	. . .	. . .	5
	≥38.10	≥1.500	≤206	≤ 32	455	66.0	. . .	. . .	400	58.0	. . .	. . .	5
2219-O	All	All	All	All	. . .	. . .	221	32.0	. . .	. . .	124	18.0	12
2219-T31 T3510[c][d]and T3511[c][d]	≤12.67	≤ 0.499	≤161	≤ 25	290	42.0	. . .	. . .	179	26.0	. . .	. . .	14
	12.70-76.17	0.500-2.999	≤161	≤ 25	310	45.0	. . .	. . .	186	27.0	. . .	. . .	14
2219-T62[e][f]	≤25.37	≤ 0.999	≤161	≤ 25	372	54.0	. . .	. . .	248	36.0	. . .	. . .	6
	≥25.40	≥1.000	≤206	≤ 32	372	54.0	. . .	. . .	248	36.0	. . .	. . .	6
2219-T81, T8510[c]and T8511[c]	â76.17	≤ 2.999	≤161	≤ 25	400	58.0	. . .	. . .	290	42.0	. . .	. . .	6
6005-T1	≤12.70	≤ 0.500	All	All	172	25.0	. . .	. . .	103	15.0	. . .	. . .	16
6005-T5	≤3.15	≤ 0.124	All	All	262	38.0	. . .	. . .	241	35.0	. . .	. . .	8
	3.18-25.40	0.125-1.000	All	All	262	38.0	. . .	. . .	241	35.0	. . .	. . .	10

6061-O	All	All	All	Al	. . .	. . .	152	22.0	. . .	. . .	110	16.0	16
6061-T1	≤15.88	≤ 0.625	All	All	179	26.0	. . .	. . .	97	14.0	. . .	. . .	16
6061-T4 T4510(c)(d)and T4511(c)(d)	All	All	All	All	179	26.0	. . .	. . .	110	16.0	. . .	. . .	16
6061-T42(e)(f)	All	All	All	All	179	26.0	. . .	. . .	83	12.0	. . .	. . .	16
6061-T51	≤15.88	≤ 0.625	All	All	241	35.0	. . .	. . .	207	30.0	. . .	. . .	8
6061-T6 T62(e)(f) T6510(c)and T6511(c)	≤6.32	≤ 0.249	All	All	262	38.0	. . .	. . .	241	35.0	. . .	. . .	8
	≥6.35	≥0.250	All	All	262	38.0	. . .	. . .	241	35.0	. . .	. . .	10
6063-O	All	All	All	All	. . .	. . .	131	19.0	. . .	. . .	. . .	. . .	18
6063-T1	≤12.70	≤ 0.500	All	All	117	17.0	. . .	. . .	62	9.0	. . .	. . .	12
	12.73-25.40	0.501-1.000	All	All	110	16.0	. . .	. . .	55	8.0	. . .	. . .	12
6063-T4 and T42(e)(f)	≤12.70	≤ 0.500	All	All	131	19.0	. . .	. . .	69	10.0	. . .	. . .	14
	12.73-25.40	0.501-1.000	All	All	124	18.0	. . .	. . .	62	9.0	. . .	. . .	14
6063-T5	≤12.70	≤ 0.500	All	All	152	22.0	. . .	. . .	110	16.0	. . .	. . .	8
	12.73-25.40	0.501-1.000	All	All	145	21.0	. . .	. . .	103	15.0	. . .	. . .	8
6063-T52	≤25.40	≤ 1.000	All	All	152	22.0	207	30.0	110	16.0	172	25.0	8
6063-T6 and T62(e)(f)	≤3.15	≤ 0.124	All	All	207	30.0	. . .	. . .	172	25.0	. . .	. . .	8

	3.18-25.40	0.125-1.000	All	All	207	30.0	. . .	. . .	172	25.0	. . .	. . .	10
6066-O	All	All	All	All	. . .	. . .	200	29.0	. . .	. . .	124	18.0	16
6066-T4, T4510(c)(d) and T4511(c)(d)	All	All	All	All	276	40.0	. . .	. . .	172	25.0	. . .	. . .	14
6066-T42(e)(f)	All	All	All	All	276	40.0	. . .	. . .	165	24.0	. . .	. . .	14
6066-T6 T6510(c) and T6511(c)	All	All	All	All	345	50.0	. . .	. . .	310	45.0	. . .	. . .	8
6066-T62(e)(f)	All	All	All	All	345	50.0	. . .	. . .	290	42.0	. . .	. . .	8
6070-T6 and T62(e)(f)	≤76.17	≤ 2.999	≤206	≤ 32	331	48.0	. . .	. . .	310	45.0	. . .	. . .	6
6105-T1	≤12.70	≤ 0.500	All	All	172	25.0	. . .	. . .	103	15.0	. . .	. . .	16
6105-T5	≤12.70	≤ 0.500	All	All	262	38.0	. . .	. . .	241	35.0	. . .	. . .	8
6162-T5, T5510(c) and T5511(c)	≤25.40	≤ 1.000	All	All	255	37.0	. . .	. . .	234	34.0	. . .	. . .	7
6162-T6 T6510(c) and T6511(c)	≤6.32	≤ 0.249	All	All	262	38.0	. . .	. . .	241	35.0	. . .	. . .	8
	6.35-12.67	0.250-0.499	All	All	262	38.0	. . .	. . .	241	35.0	. . .	. . .	10
6262-T6 T62(e)(f), T6510(c) and T6511(c)	All	All	All	All	262	38.0	·	. . .	241	35.0	. . .	. . .	10
6351-T54	≤12.70	≤ 0.500	≤129	≤ 20	207	30.0	. . .	. . .	138	20.0	. . .	. . .	10
6463-T1	≤12.70	≤ 0.500	≤129	≤ 20	117	17.0	. . .	. . .	62	9.0	. . .	. . .	12
6463-T5	≤12.70	≤ 0.500	≤129	≤ 20	152	22.0	. . .	. . .	110	16.0	. . .	. . .	8

6463-T6 and T62(e)(f)	≤3.15	≤0.124	≤129	≤20	207	30.0	. . .	. . .	172	25.0	. . .	. . .	8
	3.18-12.70	0.125-0.500	≤129	≤20	207	. . .	. . .	. . .	172	25.0	. . .	. . .	10
7001-O	All	All	All	All	. . .	. . .	290	42.0	. . .	. . .	179	26.0	10
7001-T6, T62(e)(f), T6510(c) and T6511(c)	≤6.32	≤0.249	All	All	614	89.0	. . .	. . .	565	82.0	. . .	. . .	5
	6.35-12.67	0.250-0.499	All	All	634	92.0	. . .	. . .	579	84.0	. . .	. . .	5
	12.70-50.77	0.500-1.999	All	All	648	94.0	. . .	. . .	607	88.0	. . .	. . .	5
	50.80-76.17	2.000-2.999	All	All	620	90.0	. . .	. . .	579	84.0	. . .	. . .	5
7005-T53	≤19.05	≤0.750	All	All	345	50.0	. . .	. . .	303	44.0	. . .	. . .	10
7075-O	All	All	All	All	. . .	. . .	276	40.0	. . .	. . .	165	24.0	10
7075-T6 T62(e)(f), T6510(c) and T6511(c)	≤6.32	≤0.249	All	All	538	78.0	. . .	. . .	483	70.0	. . .	. . .	7
	6.35-12.67	0.250-0.499	All	All	558	81.0	. . .	. . .	503	73.0	. . .	. . .	7
	12.70-38.07	0.500-1.499	All	All	558	81.0	. . .	. . .	496	72.0	. . .	. . .	7
	38.10-76.17	1.500-2.999	All	All	558	81.0	. . .	. . .	496	72.0	. . .	. . .	7
	76.20-114.27	3.000-4.499	≤129	≤20	558	81.0	. . .	. . .	489	71.0	. . .	. . .	7
	76.20-114.27	3.000-4.499	>129-206	>20-32	538	78.0	. . .	. . .	483	70.0	. . .	. . .	6
	114.30-127	4.500-5.000	≤206	≤32	538	78.0	. . .	. . .	469	68.0	. . .	. . .	6

7075-T73$^{(g)}$ T73510$^{(c)(g)}$ and T73511$^{(c)(g)}$	1.57-6.32	0.062-0.249	≤129	≤20	469	68.0	. . .	. . .	400	58.0	. . .	. . .	7
	6.35-38.07	0.250-1.499	≤161	≤25	483	70.0	. . .	. . .	421	61.0	. . .	. . .	8
	38.10-76.17	1.500-2.999	≤161	≤25	476	69.0	. . .	. . .	407	59.0	. . .	. . .	8
	76.20-114.27	3.000-4.499	≤129	≤20	469	68.0	. . .	. . .	393	57.0	. . .	. . .	7
	76.20-114.27	3.000-4.499	129-206	20-32	448	65.0	. . .	. . .	379	55.0	. . .	. . .	7
7075-T76$^{(h)}$ T76510$^{(c)(h)}$ and T76511$^{(c)(h)}$	≤3.15	≤0.124	All	All	496	72.0	. . .	. . .	47	62.0	. . .	. . .	7
	3.18-6.32	0.125-0.249	≤129	≤20	510	74.0	. . .	. . .	441	64.0	. . .	. . .	7
	6.35-12.67	0.250-0.499	≤129	≤20	517	75.0	. . .	. . .	448	65.0	. . .	. . .	7
	12.70-25.40	0.500-1.000	≤129	≤20	517	75.0	. . .	. . .	448	65.0	. . .	. . .	7
	12.70-25.40	0.500-1.000	≤129	≤20	517	75.0	. . .	. . .	448	65.0	. . .	. . .	7
7178-O	All	All	≤206	≤32	. . .	. . .	276	40.0	. . .	. . .	165	24.0	10
7178-T6, T6510$^{(c)}$ and T6511$^{(c)}$	≤1.55	≤0.061	All	Al	565	82.0	. . .	. . .	524	76.0	. . .	. . .	. . .
	1.58-6.32	0.062-0.249	≤129	≤20	579	84.0	. . .	. . .	524	76.0	. . .	. . .	5
	6.35-38.07	0.250-1.499	≤161	≤25	600	87.0	. . .	. . .	538	78.0	. . .	. . .	5
	38.10-63.47	1.500-2.499	≤161	≤25	593	86.0	. . .	. . .	531	77.0	. . .	. . .	5
	38.10-	1.500-	>161-	25-	579	84.0	. . .	. . .	517	75.0	. . .	. . .	5

	63.47	2.499	206	32										
	63.50-76.17	2.500-2.999	≤206	≤ 32	565	82.0	. . .	. . .	489	71.0	. . .	. . .	5	
7178-T62[(e)(f)]	≤1.55	≤ 0.061	All	All	545	79.0	. . .	. . .	503	73.0	. . .	. . .	. . .	
	1.58-6.32	0.062-0.249	≤129	≤ 20	565	82.0	. . .	. . .	510	74.0	. . .	. . .	5	
	6.35-38.07	0.250-1.499	≤161	≤ 25	593	86.0	. . .	. . .	531	77.0	. . .	. . .	5	
	38.10-63.47	1.500-2.499	≤161	≤ 25	593	86.0	. . .	. . .	531	77.0	. . .	. . .	5	
	38.10-63.47	1.500-2.499	>161-206	>25-32	579	84.0	. . .	. . .	517	75.0	. . .	. . .	5	
	63.50-76.17	2.500-2.999	≤206	≤ 32	565	82.0	. . .	. . .	489	71.0	. . .	. . .	5	
7178-T76[(h)] **T6510**[(d)(h)] **and T76511**[(d)(h)]	3.18-6.32	0.125-0.249	≤129	≤ 20	524	76.0	. . .	. . .	455	66.0	. . .	. . .	7	
	6.35-12.67	0.250-0.499	≤129	≤ 20	531	77.0	. . .	. . .	462	67.0	. . .	. . .	7	
	12.70-25.40	0.500-1.000	≤129	≤ 20	531	77.0	. . .	. . .	462	67.0	. . .	. . .	7	

Converted SI (metric) values are for information only and are not to be used for purposes of specification, acceptance, or rejection.

(a) The thickness of the cross section from which the tensile-test specimen is taken determines the applicable mechanical properties.

(b) In 50 mm (2 in.) or 4*d*. For material of such dimensions that a standard test specimen cannot be taken, or for shapes thinner than 0.062 in., the test for elongation is not required.

(c) For stress relieved tempers, the characteristics and properties other than those specified may differ somewhat from the corresponding characteristics and properties of material in the basic temper.

(d) Upon artificial aging, material in the T3/T31, T3510, T3511, T4, T4510, and T4511 tempers is capable of developing the mechanical properties applicable to material in the T81, T8510, T8511, T6, T6510, and T6511 tempers, respectively.

(e) These properties usually can be obtained by the user when the material is properly solution heat treated or solution and precipitation heat treated from the O (annealed) or F (as fabricated) temper. These properties also apply to samples of material in the O and F tempers, which are solution heat treated or solution and precipitation heat treated by the producer to determine that the material will respond to proper heat treatment. Properties attained by the user, however, may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.

(f) This temper is not available from the material producer.

(g) When subjected to stress-corrosion testing, material in this temper is capable of exhibiting no evidence of stress-corrosion cracking when exposed for a period of 30 days in the short-transverse direction at a stress level of 75% of the specified yield strength. The stress-corrosion resistance capabilities of individual lots are determined by testing the previously selected tensile-test specimens in accordance with the applicable electrical conductivity acceptance criteria.

(h) Material in this temper, when tested upon receipt by the purchaser, is capable of passing an exfoliation corrosion resistance test and the stress-corrosion resistance criteria of note (g) above except that the stress level is to be 25.0 ksi. The improved resistance to exfoliation corrosion and stress-corrosion cracking of individual lots is determined by testing the previously selected tensile-test specimens in accordance with the applicable electrical conductivity acceptance criteria.

Table 11 Mechanical-property limits for aluminum alloy die forgings

Alloy and temper	Specified thickness(a)		Specimen axis parallel to direction of grain flow						Specimen axis not parallel to direction of grain flow					Hardness, HB(c)
			Tensile strength		**Yield strength**		**Elongation (min), %(b)**		**Tensile strength**		**Yield strength**		**Elongation (min), %(b)(forging)**	
	mm	**in.**	**MPa**	**ksi**	**MPa**	**ksi**	**Coupon**	**Forging**	**MPa**	**ksi**	**MPa**	**ksi**		
1100-H112(d)	≤ 100	≤ 4	76	11.0	28	4.0	25	18	. . .	. . .	. . .	. . .	. . .	20
2014-T4	≤ 100	≤ 4	379	55.0	207	30.0	16	11	. . .	. . .	. . .	. . .	. . .	100
2014-T6	≤ 25	≤ 1	448	65.0	386	56.0	8	6	441	64.0	379	55.0	3	125
	>25-50	>1-2	448	65.0	386	56.0	(e)	6	441	64.0	379	55.0	2	125
	>50-75	>2-3	448	65.0	379	55.0	(e)	6	434	63.0	372	54.0	2	125
	>75-100	>3-4	434	63.0	379	55.0	(e)	6	434	63.0	372	54.0	2	125
2018-T61	≤ 100	≤ 4	379	55.0	276	40.0	10	7	. . .	. . .	. . .	. . .	. . .	100
2025-T6	≤ 100	≤ 4	359	52.0	228	33.0	16	11	. . .	. . .	. . .	. . .	. . .	100

2218-T61	≤100	≤4	379	55.0	276	40.0	10	7	. . .	. . .	. . .	. . .	. . .	100
2218-T72	≤100	≤4	262	38.0	200	29.0	8	5	. . .	. . .	. . .	. . .	. . .	85
2219-T6	≤100	≤4	400	58.0	262	38.0	10	8	386	56.0	248	36.0	4	100
2618-T61	≤100	≤4	400	58.0	310	45.0	6	4	379	55.0	290	42.0	4	115
3003-H112(d)	≤100	≤4	97	14.0	34	5.0	25	18	. . .	. . .	. . .	. . .	. . .	25
4032-T6	≤100	≤4	359	52.0	290	42.0	5	3	. . .	. . .	. . .	. . .	. . .	115
5083-H111(d)	≤100	≤4	290	42.0	152	22.0	. . .	14	269	39.0	138	20.0	12	. . .
5083-H112(d)	≤100	≤4	276	40.0	124	18.0	. . .	16	269	39.0	110	16.0	14	. . .
5456-H112(d)	≤100	≤4	303	44.0	138	20.0	. . .	16	. . .	. . .	. . .	. . .	. . .	. . .
6053-T6	≤100	≤4	248	36.0	207	30.0	16	11	. . .	. . .	. . .	. . .	. . .	75
6061-T6	≤100	≤4	262	38.0	241	35.0	10	7	262	38.0	241	35.0	5	80
6066-T6	≤100	≤4	345	50.0	310	45.0	12	8	. . .	. . .	. . .	. . .	. . .	100
6151-T6	≤100	≤4	303	44.0	255	37.0	14	10	303	44.0	255	37.0	6	90
7075-T6	≤25	≤1	517	75.0	441	64.0	10	7	490	71.0	421	61.0	3	135
	>25-50	>1-2	510	74.0	434	63.0	(e)	7	490	71.0	421	61.0	3	135
	>50-	>2-	510	74.0	434	63.0	(e)	7	483	70.0	414	60.0	3	135

	75	3												
	>75-100	>3-4	503	73.0	427	62.0	(e)	7	483	70.0	414	60.0	2	135
7075-T73	≤ 75	≤ 3	455	66.0	386	56.0	. . .	7	427	62.0	365	53.0	3	125
	>75-100	>3-4	441	64.0	379	55.0	. . .	7	421	61.0	359	52.0	2	125
7075-T7352	≤ 75	≤ 3	455	66.0	386	56.0	. . .	7	427	62.0	352	51.0	3	125
	>75-100	>3-4	441	64.0	365	53.0	. . .	7	421	61.0	338	49.0	2	125
7175-T74	≤ 75	≤ 3	524	76.0	455	66.0	. . .	7	490	71.0	427	62.0	4	. . .
7175-T7452	≤ 75	≤ 3	503	73.0	434	63.0	. . .	7	469	68.0	379	55.0	4	. . .
7175-T7454	≤ 75	≤ 3	517	75.0	448	65.0	. . .	7	483	70.0	421	61.0	4	. . .

Converted SI (metric) values are for information only and are not to be used for purposes of specification, acceptance, or rejection.

(a) As-forged thickness. When forgings are machined prior to heat treatment, the properties given here also will apply to the machined thickness provided that the machined thickness is not less than one-half the original (as forged) thickness.

(b) In 50 mm (2 in.) or 4*d*.

(c) For information only. Brinell hardness usually is measured on the surface of the heat treated forging using a 500 kg load and a 10 mm penetrator ball.

(d) Properties of forgings in H111 and H112 tempers depend on the equivalent cold work in the forgings. The properties listed should be attainable in any forging within the prescribed thickness range and may be considerably exceeded in some instances.

(e) When separately forged coupons are used to verify acceptability of forgings in the indicated thicknesses, the properties shown for thicknesses up through 1 in., including test-coupon elongation, apply.

Table 12 Minimum and typical room-temperature plane-strain fracture-toughness values for several high-strength aluminum alloys

Product form	Alloy and temper	Thickness		Plane-strain fracture toughness (K_{Ic})											
				L-T direction[(a)]				**T-L direction**[(b)]				**S-L direction**[(c)]			
				Minimum		**Typical**		**Minimum**		**Typical**		**Minimum**		**Typical**	
		mm	**in.**	**MPa**$\sqrt{\mathrm{m}}$	**ksi**$\sqrt{\mathrm{in.}}$	**MPa**$\sqrt{\mathrm{m}}$	**ksi**$\sqrt{\mathrm{in.}}$	**MPa**$\sqrt{\mathrm{m}}$	**ksi**$\sqrt{\mathrm{in.}}$	**MPa**$\sqrt{\mathrm{m}}$	**ksi**$\sqrt{\mathrm{in.}}$	**MPa**$\sqrt{\mathrm{m}}$	**ksi**$\sqrt{\mathrm{in.}}$	**MPa**$\sqrt{\mathrm{m}}$	**ksi**$\sqrt{\mathrm{in.}}$
Plate	7050-T7451	25.40-50.80	1.000-2.000	31.9	29.0	37	34	27.5	25.0	33	30	. . .	. . .	. . .	. . .
		50.83-76.20	2.001-3.000	29.7	27.0	36	33	26.4	24.0	32	29	23.1	21.0	28	25
		76.23-101.60	3.001-4.000	28.6	26.0	35	32	25.3	23.0	31	28	23.1	21.0	28	25
		101.63-127.00	4.001-5.000	27.5	25.0	32	29	24.2	22.0	29	26	23.1	21.0	28	25
		127.03-152.40	5.001-6.000	26.4	24.0	31	28	24.2	22.0	28	25	23.1	21.0	28	25
	7050-T7651	25.40-50.80	1.000-2.000	28.6	26.0	34	31	26.4	24.0	31	28	. . .	. . .	. . .	. . .
		50.83-76.20	2.001-3.000	26.4	24.0	. . .	. . .	25.3	23.0	. . .	. . .	22.0	20.0	26	24
	7475-			33.0	30.0	46	42	30.8	28.0	41	37	. . .	. . .	. . .	. . .

	T651														
	7475-T7651			36.3	33.0	47	43	33.0	30.0	41	37	. . .	. . .	. . .	. . .
	7475-T7351			41.8	38.0	55	50	35.2	32.0	45	41	27.5	25.0	36	33
	7075-T651			. . .	. . .	29	26	. . .	. . .	25	23	. . .	. . .	20	18
	7075-T7651			. . .	. . .	30	27	. . .	. . .	24	22	. . .	. . .	20	18
	7075-T7351			. . .	. . .	32	30	. . .	. . .	29	26	. . .	. . .	20	18
	7079-T651			. . .	. . .	30	27	. . .	. . .	25	23	. . .	. . .	18	16
	2124-T851			26.4	24.0	32	29	22.0	20.0	26	24	19.8	18.0	26	24
	2024-T351			. . .	. . .	37	34	. . .	. . .	32	29	. . .	. . .	26	24
Die forgings	7050-T74, T7452			27.5	25.0	38	35	20.9	19.0	32	29	20.9	19.0	29	26
	7175-T736, T73652			29.7	27.0	38	35	23.1	21.0	34	31	23.1	21.0	31	28

	7075-T7352	. . .	. . .	32	29	. . .	. . .	30	27	. . .	. . .	29	26
Hand forgings	7050-T7452	29.7	27.0	36	33	18.7	17.0	28	25	17.6	16.0	29	26
	7075-T73, T7352	. . .	. . .	42	38	. . .	. . .	28	25	. . .	. . .	28	25
	7175-T73652	33.0	30.0	40	36	27.5	25.0	30	27	23.1	21.0	28	25
	2024-T852	. . .	. . .	26	24	. . .	. . .	22	20	. . .	. . .	20	18
Extrusions	7050-T7651*x*	. . .	. . .	44	40	. . .	. . .	31	28	·.	·.	28	25
	7050-T7351*x*	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	7075-T651*x*	. . .	. . .	34	31	. . .	. . .	22	20	. . .	. . .	20	18
	7075-T7351*x*	. . .	. . .	33	30	. . .	. . .	26	24	. . .	. . .	22	20
	7150-T7351*x*	24.2	22.0	31	28	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	7175-T7351*x*	33.0	30.0	40	36	30.8	28.0	34	31	. . .	. . .	. . .	. . .

(a) L-T, crack plane and growth direction perpendicular to the rolling direction.

(b) T-L, crack plane and growth direction parallel to the rolling direction.

(c) S-L, short transverse fracture toughness

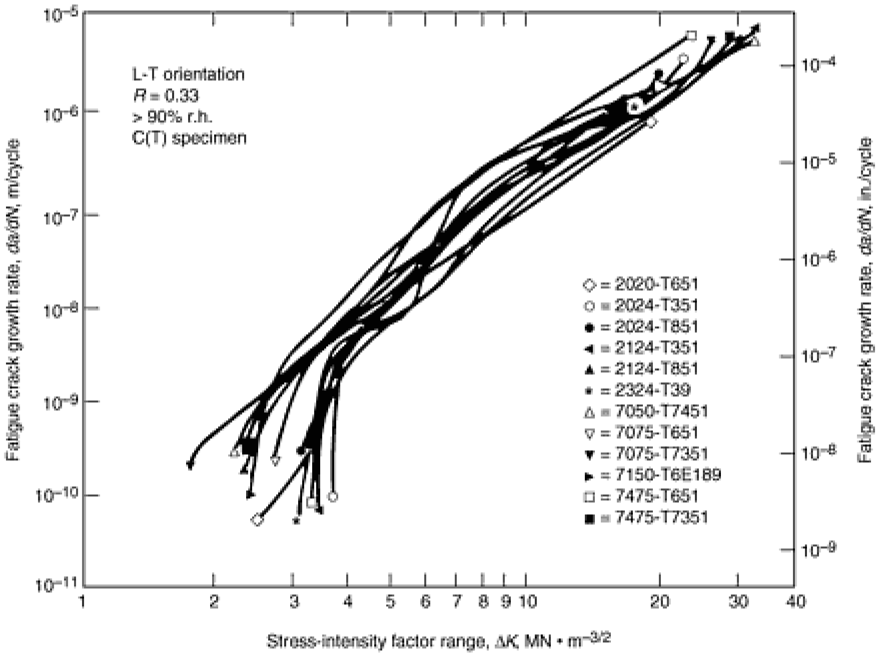


Fig. 5 Minor influences of differing microstructures on fatigue crack growth rate curves: data from twelve 2*xxx* and 7*xxx* aluminum alloys with different heat treatments

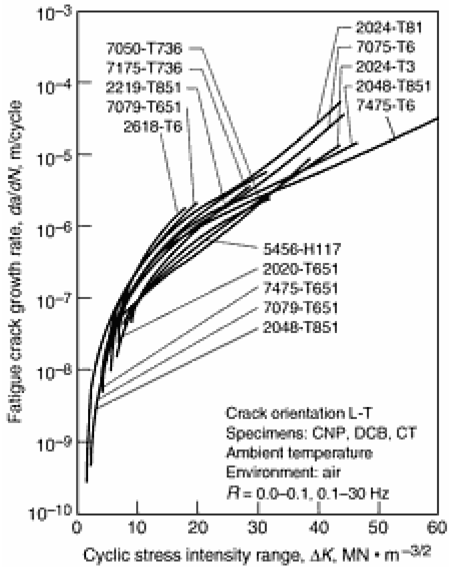


Fig. 6 Crack growth comparison. Many commercial aluminum alloys show similar fatigue crack propagation rates in air, as indicated.

Table 13 Tensile properties and fracture toughness of aluminum-lithium alloy 2090

2090 temper	Thickness		Specification	Tensile properties						Toughness		
				Direction(a)	**Ultimate tensile strength**		**Yield strength**		**Elongation in 50 min (2 in.), %**	**Direction(b) and K_c or K_{Ic}(c)**	**K_{Ic} or K_c**	
	mm	**in.**			**MPa**	**ksi**	**MPa**	**ksi**			**MPa $\sqrt{m}$**	**ksi $\sqrt{in.}$**
Sheet												
T83	0.8-3.175	0.032-0.125	AMS 4351	L	530 (550)	77 (80)	517 (517)	75 (75)	3 (6)	L-T (K_c)	(44)(d)	(40)(d)
				LT	505	73	503	73	5	...	...	...
				45 °	440	64	440	64	...	...	...	...
T83	3.2-6.32	0.126-0.249	AMS 4351	L	483	70	483	70	4	...	...	...
				LT	455	66	455	66	5	...	...	...
				45 °	385	56	385	56	...	...	...	...
T84	0.8-6.32	0.032-0.249	AMS Draft	L	495 (525)	72 (76)	455 (470)	66 (68)	3 (5)	L-T (K_c)	49 (71)(d)	45 (65)(d)
			D89	LT	475	69	415	60	5	T-L (K_c)	49(d)	45(d)
				45 °	427	62	345	50	7	...	...	...
T3(e)	...	...	(f)	LT	317 min	46 min	214 min	31 min	6 min	...	...	...

O	. . .	. . .	(f)	LT	213 max	31 max	193 max	28 max	11 min	. . .	. . .	. . .
7075-T6	. . .	. . .	. . .	L	(570)	(83)	(517)	(75)	(11)	L-T (K_c)	(71)(d)	(65)(d)
Extrusions												
T86(g)	0.0-3.15(h)	0.000-0.124(h)	AMS Draft	L	517	75	470	68	4	. . .	. . .	. . .
	3.175-6.32(h)	0.125-0.249(h)	D88BE	L	545	79	510	74	4	. . .	. . .	. . .
	6.35-12.65(h)	0.250-0.499(h)		L	550	80	517	75	5	. . .	. . .	. . .
				LT	525	76	483	70	. . .	. . .	. . .	. . .
Plate												
7075-T6	. . .	. . .	. . .	L	(565)	(82)	(510)	(74)	(11)	L-T (K_{Ic})	(27)	(25)
T81	13-38	0.50-1.50	AMS 4346	L	517 (550)	75 (80)	483 (517)	70 (75)	4 (8)	L-T (K_{Ic})	≥27 (71)	≥25 (65)
				LT	517	75	470	68	3	L-T (K_{Ic})	≥22	≥20

Typical values are given in parentheses. Data for alloy 7075-T6 are included for comparison.

(a) L, longitudinal; LT, long transverse.

(b) L-T, crack plane and direction perpendicular to the principal direction of metalworking (rolling or extrusion); T-L, crack plane and direction parallel to the direction of metalworking.

(c) K_c, plane-stress fracture toughness; K_{Ic}, plane-strain fracture toughness.

(d) Toughness limits based on limited data and typical values (in parentheses) for 405 × 1120 mm (16 × 44 in.) sheet panel.

(e) The T3 temper can be aged to the T83 or T84 temper.

(f) No end user specification.

(g) Temper registration request made to the Aluminum Association.

(h) Nominal diameter or least thickness (bars, rod, wire, shapes) or nominal wall thickness (tube)

Table 14 Tensile properties and fracture toughness of aluminum-lithium alloy 8090

Temper	Product form	Grain structure(a)	Minimum and typical(b) tensile properties						Minimum and typical(b) fracture toughness values		
			Direction	Ultimate tensile strength		0.2% yield strength		Elongation in 50 mm (2 in.), %	Fracture orientation and toughness type (K_c or K_{Ic})(c)	Toughness value(b)	
				MPa	ksi	MPa	ksi			MPa$\sqrt{m}$	ksi$\sqrt{in.}$
8090-T81 (underaged)	Damage-tolerant bare sheet <3.55 mm (0.140 in.) thick	R	Longitudinal	345-440	50-64	295-350	43-51	8-10 typ	L-T (K_c)	94-165	86-150
			Long transverse	385-450	56-65	290-325	42-47	10-12	T-L (K_c)	85 min	77 min
			45 °	380-435	55-63	265-340	38.5-49	14 typ	S-L (K_c)	. . .	. . .
8090-T8X (peak aged)	Medium-strength sheet	UR	Longitudinal	470-490	68-71	380-425	55-62	4-5	L-T (K_c)	75 typ	68 typ
			Long transverse	450-485	65-70	350-440	51-64	4-7	T-L (K_c)	. . .	. . .
			45 °	380-415	55-60	305-345	44-50	4-11	S-L (K_c)		. . .
8090-78X	Medium-strength sheet	R	Longitudinal	420-455	61-66	325-385	47-56	4-8	L-T (K_c)	. . .	. . .
			Long transverse	420-440	61-64	325-360	47-52	4-8	T-L (K_c)		. . .
			45 °	420-425	61-62	325-340	47-49	4-10	S-L (K_c)	. . .	. . .
8090-T8771, 8090-T651 (peak aged)	Medium-strength plate	UR	Longitudinal	460-515	67-75	380-450	55-65	4-6 min	L-T (K_{Ic})	20-35	18-32
			Long transverse	435 min	63 min	365 min	53 min	4 min	T-L (K_{Ic})	13-30	12-27
			Short transverse	465 typ	67 typ	360 typ	52 typ	. . .	S-L (K_{Ic})	16 typ	14.5 typ

			45 °	420 min	61 min	340 min	49 min	1-1.5 min			
8090-T8151 (underaged)	Damage-tolerant plate	UR	Longitudinal	435-450	63-65	345-370	50-54	5 min	L-T (K_{Ic})	35-49	32-45
			Long transverse	435 min	63 in	325 min	47 min	5 min	T-L (K_{Ic})	30-44	27-40
8090-T852	Die forgings with cold work, or hand forgings	UR	Longitudinal	425-495	62-72	340-415	49-60	6-8	L-T (K_{Ic})	30 typ	27 typ
			Long transverse	405-475	59-69	325-395	47-57	3-6	T-L (K_{Ic})	20 typ	18 typ
			45 °	405-450	59-65	305-395	44-57	2-6	S-L (K_{Ic})	15 typ	14 typ
8090-T8511, 8090-T6511	Extrusions	UR	Longitudinal	460-510	67-74	395-450	57-65	3-6	. . .	. . .	. . .

(a) R, recrystallized; UR, unrecrystallized.

(b) Unless otherwise specified as only a minimum (min) or a typical (typ) value, the two values given for a property represent the minimum and typical value. The minimum values are proposed by various customer and national specifications and do not reflect a uniform registration.

(c) K_c, plane-stress fracture toughness; K_{Ic}, plane-strain fracture toughness

Aluminum Foundry Products

Introduction

ALUMINUM CASTING ALLOYS are the most versatile of all common foundry alloys and generally have the highest castability ratings. As casting materials, aluminum alloys have the following favorable characteristics:

- Good fluidity for filling thin sections
- Low melting point relative to those required for many other metals
- Rapid heat transfer from the molten aluminum to the mold, providing shorter casting cycles
- Hydrogen is the only gas with appreciable solubility in aluminum and aluminum alloys, and hydrogen solubility in aluminum can be readily controlled by processing methods.
- Many aluminum alloys are relatively free from hot-short cracking and tearing tendencies.
- Chemical stability
- Good as-cast surface finish with lustrous surfaces and little or no blemishes

Aluminum alloy castings are the cost-effective answer to many needs and problems in construction of machines, equipment, appliances, vehicles and structures, usually serving a primarily mechanical function, but often combining this with an appearance or decorative function. This requires cast parts in a great variety of geometric configurations, frequently combining several different basic forms in an integral or monolithic piece. These parts include covers and housings, which may be ribbed for reinforcement or finned for heat conduction or dissipation; frames and boxlike parts; cylindrical or spherical tanks for containment of gases or fluids; brackets; pistons; wheels; disks; impellers; bulkheads; and clamps. The list of forms produced is nearly endless, and many such parts have a multitude of cored holes in bosses for fastening or as passage for fluids.

Casting Processes

Aluminum alloy castings are routinely produced by pressure-die, permanent-mold, green- and dry-sand, investment, and plaster casting. Aluminum alloys are also readily cast with vacuum, low-pressure, centrifugal, and pattern-related processes such as lost foam.

Die Casting. In die casting, which is the process used for the highest volume of production, molten metal is injected into cavities formed by heat treated steel dies and cores under pressures up to 140 MPa (20 ksi). Part size is limited only by machine capacity, and some machines are capable of producing castings weighing over 50 kg (100 lb), although casting weights up to ∼5 kg (10 lb) are more common. As-cast surfaces are very smooth and detailed; machining is generally required only to provides fits or seals with other parts. Die casting permits metal sections thinner than those obtainable by sand or permanent mold casting. High mechanical properties and resistance to fatigue can be developed in die castings without heat treatment because of the fine microstructures produced by the rapid solidification.

Alloys most frequently used in die casting differ in composition from those employed in other casting processes, because the fine die cast microstructure allows higher volume fractions of second-phase constituents, silicon, and intermetallic compounds without damaging effects on ductility or impact resistance. Iron contents up to ∼1%, which would impair both strength and ductility of other more slowly solidified castings, are quite beneficial in die casting compositions, minimizing the tendency of the aluminum to "solder" or adhere to the steel dies. Common die cast aluminum alloys and their typical applications include:

Alloy 308.0	**Lawnmower housings, gear cases, and cylinder heads for air-cooled engines**
Alloy A380.0	Streetlamp housings, typewriter frames, and dental equipment
Alloy 360.0	Frying skillets, cover plates, instrument cases, and parts requiring corrosion resistance
Alloy 413.0	Outboard motor parts such as pistons, connecting rods, and housings
Alloy 518.0	Escalator parts, conveyor components, aircraft and marine hardware, and fittings

Permanent mold casting employs metal molds and cores with either gravity or low-pressure introduction of molten metal. Most permanent mold castings weigh less than 10 kg (20 lb), but castings weighing up to 25 kg (50 lb), and sometimes even up to 100 kg (200 lb), are not uncommon. Permanent mold castings have smoother surfaces than those of sand castings and exhibit superior pressure tightness. Tapered metal cores are used to form straight-wall cavities, and collapsible metal cores are used to form internal ribs and undercuts, which also can be formed by expendable (dry sand or plastic) cores. When the latter are used, the process is referred to as semi-permanent mold casting. Mechanical properties (including fatigue resistance) of permanent mold castings are very high because of the fine microstructure and the capability for heat treatment.

Some common aluminum permanent mold casting alloys, and typical products cast from them, are presented in the following table:

Alloy 336.0	**Automotive pistons**
Alloys 355.0, C355.0, A357.0	Timing gears, impellers, compressors, and aircraft and missile components requiring high strength
Alloys 356.0, A356.0	Machine tool parts, aircraft wheels, pump parts, marine hardware, valve bodies
Alloy B443.0	Carburetor bodies, waffle irons
Alloy 513.0	Ornamental hardware and architectural fittings

Other aluminum alloys commonly used for permanent mold castings include 296.0, 319.0, and 333.0. Specifications for permanent mold castings are cross referenced in Table 1.

Table 1 Cross-reference chart of frequently used specifications for aluminum alloy sand and permanent mold (PM) castings

Alloy		Federal		ASTM[(a)]		SAE[(b)]	AMS or MIL-21180c
Aluminum Association No.	**Former designation**	**QQ-A-601E (sand)**	**QQ-A-596d (PM)**	**B 26 (sand)**	**B 108 (PM)**		
208.0	108	108	. . .	CS43A	CS43A	. . .	. . .
213.0	C113	. . .	113	CS74A	CS74A	33	. . .
222.0	122	122	122	CG100A	CG100A	34	. . .
242.0	142	142	142	CN42A	CN42A	39	4222
295.0	195	195	. . .	C4A	. . .	38	4231
296.0	B295.0	. . .	B195	. . .	. . .	380	. . .
308.0	A108	. . .	A108	. . .	. . .	. . .	. . .
319.0	319, Allcast	319	319	SC64D	SC64D	326	. . .
328.0	Red X-8	Red X-8	. . .	SC82A	. . .	327	. . .

332.0	F332.0	. . .	F132	. . .	SC103A	332	. . .
333.0	333	. . .	333	. . .	. . .	. . .	. . .
336.0	A332.0	. . .	A132	. . .	SN122A	321	. . .
354.0	354	. . .	. . .	. . .	. . .	. . .	C354(c)
355.0	355	355	355	SC51A	SC51A	322	4210
C355.0	C355	. . .	C355	. . .	SC51B	355	C355(c)
356.0	356	356	356	SG70A	SG70A	323	(d)
A356.0	A356	. . .	A356	. . .	SG70B	336	A356(c)
357.0	357	. . .	357	. . .	. . .	. . .	4241
A357.0	A357	. . .	. . .	. . .	. . .	. . .	A357(c)
359.0	359	. . .	. . .	. . .	. . .	. . .	359(c)
B443.0	43	43	43	S5A	S5A	. . .	. . .
512.0(e)	B514.0	B214	. . .	GS42A	GS42A	. . .	. . .
513.0	A514.0	. . .	A214	. . .	GZ42A	. . .	. . .
514.0	214	214	. . .	G4A	. . .	320	. . .
520.0	220	220	. . .	G10A	. . .	324	4240
535.0	Almag 35	Almag 35	. . .	GM70B	GM70B	. . .	4238
705.0	603, Ternalloy 5	Ternalloy 5	Ternalloy 5	ZG32A	ZG32A	311	. . .
707.0	607, Ternalloy 7	Ternalloy 7	Ternalloy 7	ZG42A	ZG42A	312	. . .
710.0	A712.0	A612	. . .	ZG61B	. . .	313	. . .
712.0	D712.0	40E	. . .	ZG61A	. . .	310	. . .

713.0	613, Tenzaloy	Tenzaloy	. . .	ZC81A	. . .	315	. . .
771.0	Precedent 71A	Precedent 71A	. . .	. . .	. . .	. . .	. . .
850.0	750	750	750	. . .	. . .	. . .	. . .
851.0	A850.0	A750	A750	. . .	. . .	. . .	. . .
852.0	B850.0	B750	B750	. . .	. . .	. . .	. . .

(a) Former designations. ASTM adopted the Aluminum Association designation system in 1974.

(b) Former designations used in SAE specifications J452 and/or J453. In 1990, SAE J452 adopted the ANSI/Aluminum Association numbering system for alloys. SAE J453-1986 has also superceded SAE J452.

(c) Designation in MIL-21180c.

(d) Alloy 356.0 is specified in AMS 4217, 4260, 4261, 4284, 4285, and 4286.

(e) Alloy 512.0 is no longer active; it is included for reference purposes only.

Sand casting is in some ways the most versatile foundry method, with few limitations on the type of alloy that can be used or on part size or shape and extent of coring to form internal cavities and passages. This process is employed for relatively large parts, when required quantities are small, or when the design or the alloy dictates use of an expendable mold material. Size or weight limitations are generally established by melting, metal, or mold-handling capabilities. Sand castings weighing over 9,000 kg (18,000 lb) with dimensions of 5.5 m (18 ft) and over have been produced. As-cast surfaces are rougher than for other processes, and required dimensional tolerances are greater. A full range of mechanical properties is available because both non-heat-treatable alloys and heat treatable alloys of high strength capability can be used.

Typical products made from some common aluminum sand casting alloys include:

Alloy C355.0	**Air-compressor fittings, crankcases, and gear housings**
Alloy A356.0	Automobile transmission cases, oil pans, and rear-axle housings
Alloy 357.0	Pump bodies and cylinder blocks for water-cooled engines
Alloy 443.0	Pipe fittings, cooking utensils, and ornamental marine fittings

Alloy 520.0	Aircraft fittings, truck and bus frame components, levers, and brackets
Alloy 713.0	General-purpose casting alloy for applications requiring strength without heat treatment or involving brazing

Other aluminum alloys commonly used for sand castings include 319.0, 355.0, 356.0, 514.0, and 535.0. Specifications for sand-cast aluminum alloys are cross referenced in Table 1.

Shell Mold Casting. In this process the mold cavity is formed by a shell of resin-bonded sand only 10 to 20 mm (0.4 to 0.8 in.) thick--much thinner and lighter than the massive molds commonly used in sand foundries. Shell mold castings surpass ordinary sand castings in surface finish and dimensional accuracy and cool at slightly higher rates. Equipment costs are higher, and the size and complexity of castings that can be produced are more limited.

Plaster and Investment Casting. These processes are capable of producing intricate, thin-section parts with great dimensional accuracy, sharp reproduction of fine detail, and very smooth surfaces. Most castings produced by these methods are small and of thin section. Other mold materials or composite molds are generally required to provide adequate chilling capacity for castings having thick sections.

Composite Mold Casting. Use of more than one mold material having different heat-extraction (chilling) capabilities is the basis for composite mold casting. The mold materials are arranged to optimize the sequence of solidification from one part of the casting to another, providing increased soundness and strength with good dimensional control.

Evaporative (lost-foam) pattern casting (EPC) is a sand casting process that uses an unbonded sand mold with an expendable polystyrene pattern placed inside of the mold. This process is somewhat similar to investment casting in that an expendable material can be used to form relatively intricate patterns in a surrounding mold material. Unlike investment casting, however, EPC involves a polystyrene foam pattern that vaporizes during the pouring of molten metal into a surrounding mold of unbonded sand. With investment casting, a wax or plastic pattern is encased in a ceramic mold and removed by heat prior to the filling of the mold with molten metal.

Centrifugal Casting. Axisymmetric parts, such as those of tubular shape, are sometimes produced by true centrifugal casting in a metal mold. For nonsymmetrical shapes, mold filling can be assisted by centrifuging the molten metal into the mold cavity. In this process, multiple mold cavities are usually arranged around a central pouring sprue.

Continuous Casting. Long shapes of simple cross section (such as round, square, and hexagonal rods) can be produced by continuous casting, which is done in a short, bottomless, water-cooled metal mold. The casting is continuously withdrawn from the bottom of the mold; because the mold is water cooled, cooling rate is very high. As a result of continuous feeding, castings generally are free of porosity. In most instances, however, the same product can be made by extrusion at approximately the same cost and with better properties, and thus use of continuous casting is limited. The largest application of continuous casting is production of ingot for rolling, extrusion, or forging.

Hybrid permanent mold processes include both squeeze casting (liquid-metal forging) and semi-solid forming. Both of these processes offer net shape capabilities, but produce components that have mechanical properties well in excess of permanent mold castings and approaching those of forgings. Automotive components made from alloys 356 and 357 have been produced by these methods.

Selection of Casting Process

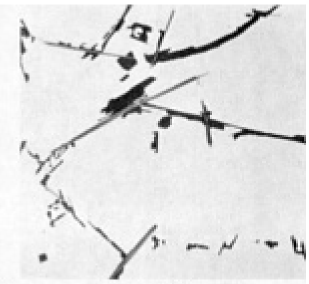
Many factors affect the selection of a casting process for producing a specific part. In many cases the decision is influenced strongly by geometric configuration and design features, which determine the feasibilities of the different processes. When the casting can be produced by several of the available methods, relative weights, quantity requirements, and unit costs are frequently determinative. Selection can also depend on quality factors, such as soundness, pressure tightness, surface finish, machining requirements, mechanical properties, environmental service conditions, or special conditions of installation, assembly, or joining (such as by welding or brazing). Close cooperation between designers and potential producers is essential in coupling design and process to achieve the most cost-effective results. As with all procurement, availability and delivery may sometimes be prevailing factors.

Table 2 lists the principal technical factors of comparison among the basic sand, permanent mold, and die casting processes. Figure 1, presents the comparative microstructures of an Al-5%Si alloy (443.0 type) cast by these three processes and the corresponding typical tensile properties. These differences may be important factors in process selection.

Table 2 Factors affecting selection of casting process for aluminum alloys

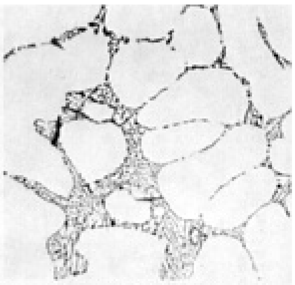
Factor	Casting process		
	Sand casting	**Permanent mold casting**	**Die casting**
Cost of equipment	Lowest cost if only a few items required	Less than die casting	Highest
Casting rate	Lowest rate	11 kg/h (25 lb/h) common; higher rates possible	4.5 kg/h (10 lb/h) common; 45 kg/h (100 lb/h) possible
Size of casting	Largest of any casting method	Limited by size of machine	Limited by size of machine
External and internal shape	Best suited for complex shapes where coring is required	Simple sand cores can be used, but more difficult to insert than in sand castings	Cores must be able to be pulled because they are metal; undercuts can be formed only by collapsing cores or loose pieces
Minimum wall thickness	3.0-5.0 mm (0.125-0.200 in.) required; 4.0 mm (0.150 in.) normal	3.0-5.0 mm (0.125-0.200 in.) required; 3.5 mm (0.140 in.) normal	1.0-2.5 mm (0.100-0.040 in.); depends on casting size
Types of cores	Complex baked sand cores can be used	Reusable cores can be made of steel, or nonreuseable baked cores can be used	Steel cores; must be simple and straight so they can be pulled
Tolerance obtainable	Poorest; best linear tolerance is 300 mm/m (300 mils/in.)	Best linear tolerance is 10 mm/m (10 mils/in.)	Best linear tolerance is 4 mm/m (4 mils/in.)
Surface finish	6.5-12.5 μm (250-500 μin.)	4.0-10 μm (150-400 μin.)	1.5 μm (50 μin.); best finish of the three casting processes
Gas porosity	Lowest porosity possible with good technique	Best pressure tightness; low porosity possible with good technique	Porosity may be present
Cooling rate	0.1-0.5 °C/s (0.2-0.9 °F/s)	0.3-1.0 °C/s (0.5-1.8 °F/s)	50-500 °C/s (90-900 °F/s)
Grain size	Coarse	Fine	Very fine on surface
Strength	Lowest	Excellent	Highest, usually used in the as-cast condition
Fatigue	Good	Good	Excellent

properties			
Wear resistance	Good	Good	Excellent
Overall quality	Depends on foundry technique	Highest quality	Tolerance and repeatability very good
Remarks	Very versatile in size, shape, and internal configurations	. . .	Excellent for fast production rates



(a) Sand cast 443.0-F

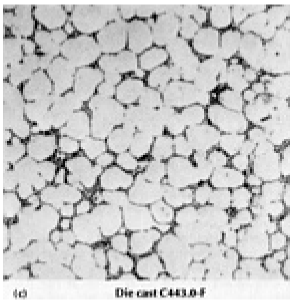
Typical tensile properties				**Elongation, %**
Tensile strength		**Yield strength**		
MPa	**ksi**	**MPa**	**ksi**	
130	19	55	8	8



(b) Permanent mold cast B443.0-F

Typical tensile properties		Elongation, %
Tensile	**Yield**	

strength		**strength**		
MPa	**ksi**	**MPa**	**ksi**	
160	23	60	9	10



Typical tensile properties				Elongation, %
Tensile strength		**Yield strength**		
MPa	**ksi**	**MPa**	**ksi**	
230	33	110	16	9

Fig. 1 Al-5% Si alloy microstructures resulting from different solidification rates characteristic of different casting processes. Dendrite cell size and constituent particle size decrease with increasing cooling rate, from sand cast to permanent-mold cast to die cast. Etchant, 0.5% hydrofluoric acid. 500×

Unit costs are highly quality dependent because of tooling amortization costs. In general, the lower the tooling investment (patterns, molds, dies, and auxiliary equipment), the greater the cost of producing each piece. When only a few pieces are required, the method involving the least expensive tooling will result in the lowest unit cost, even though the cost of casting each piece is high. For very large production runs, where the tooling cost is shared by a large number of castings, more elaborate tooling decreases unit casting cost sufficiently to outweigh the initial investment. A typical analysis for production of a small part by various casting processes (sand, permanent mold, die, and investment casting) and by die forging, on the basis of relative unit cost versus quantity required, is illustrated graphically in Fig. 2.

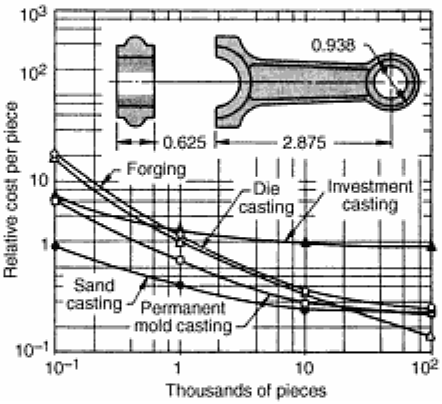


Fig. 2 Relative unit costs of producing a small connecting rod in various quantities by four casting processes and by forging. Tooling costs appropriate to process and quantity requirements are assumed. Dimensions are in inches.

Design and Function. The objective of casting design for mechanical function is to prevent failure due to the loads and stresses of normal operation plus those resulting from abuse and accidents. Basic principles applicable to any mechanical metal part apply, such as avoidance of sharp corners and other stress-concentrating features. Sections varying in thickness must be carefully blended, and wide thickness variations must be avoided. Thick sections isolated by thin sections cannot be "fed," and internal unsoundness or surface shrinkage can result. Each process has generally applicable minimum-section-thickness requirements, but these vary considerably depending on the area of the section and the character of surrounding features. As indicated previously, there is no substitute for experience in linking design, producibility and quality, and early consultation with foundry personnel during casting design will save time and avoid difficulties.

Casting Quality. When applied to castings, the term "quality" embraces many features including fidelity of reproduction of intended shape and dimensions, surface continuity and smoothness, as well as degree of soundness (freedom from cracks, porosity, and surface imperfections). These quality features are affected by design, casting process, alloy, and foundry procedures and control. Metallurgical microstructures are highly dependent on local rates of solidification and may vary substantially from one part of the casting to another. Solidification rate depends on section thickness and on the heat-extraction (chilling) capability of the mold or die, which in turn depends on two factors--the mold or die material, and the degree of persistence of thermal contact between the solidifying metal and the cavity surfaces. This obviously is process dependent, because not only the mold materials but also the pressure of the metal in the cavity vary with the process. Thus solidification rates increase in the following order: plaster, sand, permanent mold, centrifugal, and die casting. Table 2 lists some nominal cooling rates.

Grain size is refined by increasing solidification rate but is also highly dependent on the presence of grain-refining elements (principally titanium and boron) in the alloy. Even more importantly, solidification rate establishes the fineness of the microstructure--that is, the size and spacing of dendrites and the size and distribution of second-phase constituent particles. Relative values of dendrite-arm spacing (DAS), the most convenient feature for metallographic measurement and quantification, are closely correlated with constituent size and the effects on strength and ductility. Nominal DAS values are listed for three casting processes (sand, permanent mold, and die casting) in Table 2, and the correlation between mechanical properties and microstructure for alloy 443.0-F is apparent in Figure 1.

In general, two types of porosity can occur in cast aluminum: gas porosity and shrinkage porosity. Gas porosity, which generally is fairly spherical in shape, results either from precipitation of hydrogen during solidification (because the solubility of this gas is much higher in the molten metal than in the solid metal) or from occlusion of gas bubbles during the high-velocity injection of molten metal in die casting. The other source of porosity is the liquid-to-solid shrinkage, which frequently takes the form of interdendritically distributed voids. These voids can be enlarged by hydrogen, and, because larger dendrites result from slower solidification, the size of such porosity also increases as solidification rate decreases. It is not fair to the various processes to establish inherent ratings with respect to anticipated porosity, because castings made by any process can vary substantially in soundness--from nearly completely sound to very unsound--depending on casting size and design as well as on foundry techniques.

All aspects of casting quality are affected significantly by alloy composition, and each process tends to operate most effectively, providing the highest productivity and quality, with a specific alloy or with alloys of a specific type. It is on the basis of experience with this factor that certain alloys are indicated as being intended for use primarily in sand, permanent mold, or die casting. Some alloys are used for several (or all) processes.

Alloy Systems

Aluminum casting alloys are based on the same alloy systems as those of wrought aluminum alloys, are strengthened by the same mechanisms (with the general exception of strain hardening), and are similarly classified into non-heat-treatable and heat treatable types. The major difference is that the casting alloys used in the greatest volumes contain alloying additions of silicon far in excess of the amounts in most wrought alloys.

Alloy selection for some types of applications is purely a matter of meeting functional requirements. For example, where very high electrical conductivity is essential, as in the pressure-cast integral conductor bars and collector rings of electric-motor rotors, only the unalloyed 1*xx.x* aluminum compositions can be used. For marine and salt water exposures, highest resistance to corrosion requires use of 5*xx.x* aluminum-magnesium alloys, as do many decorative, bright-finish, and food-processing-machinery applications.

The 2*xx.x* aluminum-copper group includes compositions capable of developing the highest strengths among all casting alloys, and these alloys are used where this is a predominant requirement. These alloys (A201.0, 202.0, 204.0, and A206.0) contain 4 to 6% Cu and 0.25 to 0.35% Mg, with highly restrictive impurity (iron and silicon) limits, and in some cases also contain 0.25 to 0.35% Mn or Cr and (in alloys 201.0, A201.0, and 202.0) 0.7% Ag. Good casting design and foundry techniques must be employed to realize full mechanical-property capabilities and consistently high quality for these alloys.

The 2*xx.x* alloys also have the highest strengths and hardnesses of all casting alloys at elevated temperatures (to 300 °C, or 600 °F), and this factor accounts for their use in some applications. Alloys 222.0, 224.0, 238.0, 240.0, 242.0, and 243.0, some with higher copper contents up to 2% Mg (6% in alloy 240.0) and additions of manganese, nickel, vanadium, and/or zirconium, are used primarily at elevated temperatures.

Heat treatment is required with the 2*xx.x* alloys for development of highest strength and ductility and must be properly applied to ensure high resistance to stress-corrosion cracking. General corrosion resistance of these alloys is lower than those of other types of casting alloys, and protection by surface coatings is required in critical applications.

The 7*xx.x* aluminum-zinc-magnesium alloys are notable for their combinations of good finishing characteristics, good general corrosion resistance, and the capability of developing high strength through natural aging without heat treatment. The 8*xx.x* aluminum-tin alloys are special-purpose compositions used for sleeve bearings and bushings.

Almost all of the alloys in the 2*xx.x, 5xx.x, 7xx.x,* and 8*xx.x* groups are limited with respect to the casting configurations that can be produced with good recovery and quality. Greater care and adaptations in mold design are required to produce highest-quality castings with these alloys than with those of the 3*xx.x* and 4*xx.x* groups that have higher silicon contents.

Silicon is the alloying element that literally makes the commercial viability of the high-volume aluminum casting industry possible. Silicon contents from ~4% to the eutectic level of ~12% reduce scrap losses, permit production of much more intricate designs with greater variations in section thickness, and yield castings with higher surface and internal quality. These benefits derive from the effects of silicon in increasing fluidity, reducing cracking, and improving feeding to minimize shrinkage porosity.

Figure 3 shows the complete phase diagram of the binary aluminum-silicon system. This is a simple eutectic system with limited terminal solubility and is the basis for the 4*xx.x* alloys. Metallographic structures of the pure components and of several intermediate compositions show typical morphologies. The intermediate compositions are mixtures of aluminum containing ~1% Si in solid solution as the continuous phase, with particles of essentially pure silicon. Alloys with <12% Si are referred to as "hypoeutectic," those with close to 12% Si as "eutectic," and those with >12% Si as "hypereutectic."

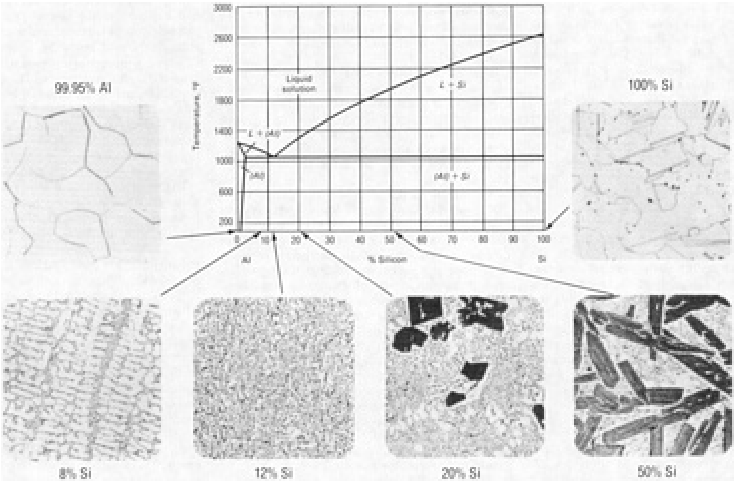


Fig. 3 Aluminum-silicon phase diagram and cast microstructures of pure components and of alloys of various compositions. Alloys with less than 12% Si are referred to as hypoeutectic, those with close to 12% Si as eutectic, and those with over 12% Si as hypereutectic.

Resistance to cracking during casting is favored by a small range of solidification temperature, which drops from ~78 °C (140 °F) at 1% Si to zero at ~12% Si. Good feeding characteristics to minimize shrinkage porosity are benefited by a profile of volume fraction solidified versus temperature, which is weighted toward the lower portion of the temperature range--that is, toward increased eutectic. In the binary system, under the nonequilibrium conditions of casting, the volume fraction of eutectic increases linearly from ~0 to 1 as silicon content increases from 1 to 12%.

The highest-volume-usage alloys are those in the 3xx.x group, which, in addition to silicon, contain magnesium, copper, or both, and in specific cases, supplementary additions of nickel or beryllium. In general, they fall into one of three types: Al-Si-Mg, Al-Si-Cu, or Al-Si-Cu-Mg. Silicon contents range from 5 to 22%. Copper contents range from 0% (alloys 356.0 through 361.0) to a maximum of 4.5%. Most of these alloys have nominal magnesium contents ranging from as low as 0.3% to ~0.6% for the high-strength compositions and 1.0% for the piston alloys 332.0 and 336.0. The principal alloys of this group requiring low magnesium contents (0.10% maximum) are the die casting compositions 380.0 through 384.0.

Both copper and magnesium increase strength and hardness in the as-cast (F) temper through increased solid-solution hardening. Much greater increases are afforded by artificial aging only (T5-type tempers) or by complete solution plus artificial aging treatments (T6- or T7-type tempers). Depending on composition, the precipitation hardening is the result of precipitate structures based on Mg_2Si, Al_2Cu, Al_2CuMg, or combinations of these phases. The alloys containing both copper and magnesium have higher strengths at elevated temperatures.

Higher-silicon-content alloys are preferred for casting by the permanent mold and die casting processes. The thermal expansion coefficient decreases with increasing silicon and nickel contents. A low expansion coefficient is beneficial for engine applications such as pistons and cylinder blocks. When the silicon content exceeds 12%, as in alloys 390.0 through 393.0, primary silicon crystals are present and, if fine and well distributed, enhance wear resistance.

Alloys of the 4*xx.x* group, based on the binary aluminum-silicon system and containing from 5 to 12% Si, find many applications where combinations of moderate strength and high ductility and impact resistance are required. Bridge railing support castings are a representative example.

Alloys of the 8*xx.x* group contain ~6% Sn and small amounts of copper and nickel for strengthening. These alloys were developed for bearing applications (tin imparts lubricity), for example, connecting rods and crankcase bearings for diesel engines.

Mechanical Properties

Typical mechanical properties of various aluminum casting alloys are given in the compilations of the following article, "Properties of Aluminum Castings." These typical values should be used only for assessing the suitability of an alloy for a particular application and not for design purposes. Design-stress values are significantly below typical properties as discussed in the section "Mechanical Test Methods" later in this article. Actual design strength depends on several factors, including:

- Section size
- Expected degree of porosity
- Presence of sharp corners
- Probability of cyclic loading in service

Minimum mechanical property limits are usually defined by the terms of general procurement specifications, such as those developed by government agencies and technical societies. These documents often specify testing frequency, tensile bar type and design, lot definitions, testing procedures, and the limits applicable to test results. By references to general process specifications, these documents also invoke standards and limits for many additional supplier obligations, such as specific practices and controls in melt preparation, heat treatment, radiographic and liquid penetrant inspection, and test procedures and interpretation.

Mechanical Test Methods. Typical and minimum mechanical-property values commonly reported for castings of particular aluminum alloys are determined using separately cast test bars that are $\frac{1}{2}$ in. diameter (for sand and permanent mold castings) or $\frac{1}{4}$ in. diameter (for die castings). As such, these values represent properties of sound castings, 13 or 6 mm ($\frac{1}{2}$ or $\frac{1}{4}$ in.) in section thickness, made using normal casting practice; they do not represent properties in all sections and locations of full-size production castings. Typical and minimum properties of test bars, however, are useful in determining relative strengths of the various alloy/temper combinations. Minimum properties--those values listed in applicable specifications--apply, except where otherwise noted, only to separate cast test bars. These values, unlike minimum values based on bars cut from production castings, are not usable as design limits for production castings. However, they can be useful in quality assurance. Actual mechanical properties, whether of separately cast test bars or of full-size castings, are dependent on two main factors:

- Alloy composition and heat treatment
- Solidification pattern and casting soundness

Some specifications for sand, permanent mold, plaster, and investment castings have defined the correlation between test results from specimens cut from the casting and separately cast specimens. A frequent error is the assumption that test values determined from these sources should agree. Rather, the properties of separately cast specimens should be expected to be superior to those of specimens machined from the casting. In the absence of more specific guidelines, one rule of thumb defines the average tensile and yield strengths of machined specimens as not less than 75% of the minimum requirements for separately cast specimens and elongation as not less than 25% of the minimum requirement. These relations may be useful in establishing the commercial acceptability of parts in dispute.

Test Specimens. Accurate determination of mechanical properties of aluminum alloy castings (or of castings of any other metal) requires proper selection of test specimens. For most wrought products, a small piece of the material often is considered typical of the rest, and mechanical properties determined from that small piece also are considered typical. Properties of castings, however, vary substantially from one area of a given casting to another, and may vary from casting to casting in a given heat.

If castings are small, one from each batch can be sacrificed and cut into test bars. If castings are too large to be economically sacrificed, test bars can be molded as an integral part of each casting, or can be cast in a separate mold.

Usually, test bars are cast in a separate mold. When this is done, care must be taken to ensure that the metal poured into the test-bar mold is representative of the metal in the castings that the test bars are supposed to represent. In addition, differences in pouring temperature and cooling rate, which can make the properties of separately cast test bars different from those of production castings, must be avoided.

For highly stressed castings, integrally cast test bars are preferable to separately cast bars. When integrally cast bars are selected, however, gating and risering must be designed carefully to ensure that test bars and castings have equivalent microstructure and integrity. Also, if there are substantial differences between test-bar diameter and wall thickness in critical areas of the casting, use of integrally cast test panels equal in thickness to those critical areas, instead of standard test bars, should be considered.

ASTM E 8 defines the test bars suitable for evaluation of aluminum castings. The use of test bars cut from die castings is not recommended; simulated service (proof) testing is considered more appropriate.

Premium engineered castings provide higher levels of quality and reliability than are found in conventionally produced parts. These castings may display optimum performance in one or more of the following characteristics: mechanical properties (determined by test coupons machined from representative parts), soundness (determined radiographically), dimensional accuracy, and finish. However, castings of this classification are notable primarily for mechanical property attainment that reflects extreme soundness, fine dendrite arm spacing, and well-refined grain structure. These technical objectives require the use of chemical compositions competent to display premium engineering properties. Alloys considered to be premium engineered compositions appear in separately negotiated specifications or in specifications such as military specification MIL-A-21180, which is extensively used in the United States for premium engineered casting procurement.

Alloys commonly considered premium by definition and specification are 201.0, C355.0, A206.0, A356.0, 224.0, A357.0, 249.0, 358.0, and 354.0. All alloys employed in premium engineered casting work are characterized by optimum concentrations of hardening elements and restrictively controlled impurities. Although any alloy can be produced in cast form with properties and soundness conforming to a general description of premium values relative to corresponding commercial limits, only those alloys demonstrating yield strength, tensile strength, and especially elongation in a premium range belong in this discussion. They fall into two categories: high-strength aluminum-silicon compositions and those alloys of the 2*xx* series, which, by restricting impurity element concentrations, provide outstanding ductility, toughness, and tensile properties with notably poorer castability.

Hot isostatic pressing of aluminum castings reduces porosity and can thus decrease the scatter in mechanical properties. The method also makes possible the salvaging of castings that have been scrapped for reasons of internal porosity, thereby achieving improved foundry recovery. This advantage is of more significant importance in the manufacture of castings subject to radiographic inspection when required levels of soundness are not achieved in the casting process. The development of hot isostatic pressing is pertinent to the broad range of premium castings, but is especially relevant for the more difficult-to-cast aluminum-copper series. Figure 4 shows the improvement in the fatigue life of Al-Cu cast alloy A201-T7 as the result of hot isostatic pressing.

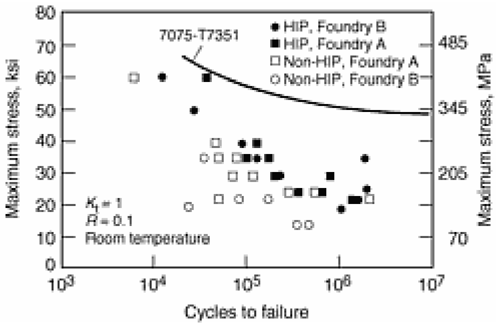


Fig. 4 Stress-life fatigue data for alloy A201-T7 castings with and without hot isostatic pressing (HIP).

Properties of Aluminum Castings

Table 1 Typical physical properties of aluminum casting alloys

Aluminum Association No.	Temper[(a)]	Specific gravity[(b)]	Density[(b)]		Approximate melting range		Electrical conductivity, %IACS	Thermal conductivity at 25 °C (77 °F), cgs units	Coefficient of thermal expansion per °C × 10^{-6} (per °F × 10^{-6})			
			kg/m³	**lb/in.³**	**°C**	**°F**			**20 to 100 °C**	**68 to 212 °F**	**20 to 300 °C**	**68 to 570 °F**
201.0	T6 (S)	2.80	2796	0.101	570-650	1060-1200	27-32	0.29	34.7	19.3	44.5	24.7
	T7 (P)	2.80	2796	0.101	570-650	1060-1200	32-34	0.29	34.7	19.3	44.5	24.7
206.0	. . .	2.8	2796	0.101	570-650	1060-1200	. . .	0.29	. . .	. . .	. . .	. . .
A206.0	. . .	2.8	2796	0.101	570-650	1060-1200	. . .	0.29	. . .	. . .	. . .	. . .
208.0	F (S)	2.79	2796	0.101	520-630	970-1170	31	0.29	22.0	12.2	23.9	13.3
	O (S)	2.79	2796	0.101	520-630	970-1170	38	0.35	. . .	. . .	. . .	. . .
222.0	F (P)	2.95	2962	0.107	520-625	970-1160	34	0.32	221.	12.3	23.6	13.1
	O (S)	2.95	2962	0.107	520-625	970-1160	41	0.38	. . .	. . .	. . .	. . .
	T61 (S)	2.95	2962	0.107	520-625	970-1160	33	0.31	22.1	12.3	23.6	13.1
224.0	T62 (S)	2.81	2824	0.102	550-645	1020-1190	30	0.28	. . .	. . .	. . .	. . .
238.0	F (P)	2.95	1938	0.107	510-600	950-1110	25	0.25	21.4	11.9	22.9	12.7
240.0	F (S)	2.78	2768	0.100	515-605	960-1120	23	0.23	22.1	12.3	24.3	13.5
242.0	O (S)	2.81	2823	0.102	530-	990-	44	0.40	. . .	. . .	. . .	. . .

					635	1180						
	T77 (S)	2.81	2823	0.102	525-635	980-1180	38	0.36	22.1	12.3	23.6	13.1
	T571 (P)	2.81	2823	0.102	525-635	980-1180	34	0.32	22.5	12.5	24.5	13.6
	T61 (P)	2.81	2823	0.102	525-635	980-1180	33	0.32	22.5	12.5	24.5	13.6
295.0	T4 (S)	2.81	2823	0.102	520-645	970-1190	35	0.33	22.9	12.7	24.8	13.8
	T62 (S)	2.81	2823	0.102	520-645	970-1190	35	0.34	22.9	12.7	24.8	13.8
296.0	T4 (P)	2.80	2796	0.101	520-630	970-1170	33	0.32	22.0	12.2	23.9	13.3
	T6 (P)	2.80	2796	0.101	520-630	970-1170	33	0.32	22.0	12.2	23.9	13.3
	T62 (S)	2.80	2796	0.101	520-630	970-1170	33	0.32	. . .	. . .	. . .	. . .
308.0	F (P)	2.79	2796	0.101	520-615	970-1140	37	0.34	21.4	11.9	22.9	12.7
319.0	F (S)	2.79	2796	0.101	520-605	970-1120	27	0.27	21.6	12.0	24.1	13.4
	F (P)	2.79	2796	0.101	520-605	970-1120	28	0.28	21.6	12.0	24.1	13.4
324.0	F (P)	2.67	2658	0.096	545-605	1010-1120	34	0.37	21.4	11.9	23.2	12.9
332.0	T5 (P)	2.76	2768	0.100	520-580	970-1080	26	0.25	20.7	11.5	22.3	12.4
333.0	F (P)	2.77	2768	0.100	520-585	970-1090	26	0.25	20.7	11.5	22.7	12.6
	T5 (P)	2.77	2768	0.100	520-585	970-1090	29	0.29	20.7	11.5	22.7	12.6

	T6 (P)	2.77	2768	0.100	520-585	970-1090	29	0.28	20.7	11.5	22.7	12.6
	T7 (P)	2.77	2768	0.100	520-585	970-1090	35	0.34	20.7	11.5	22.7	12.6
336.0	T551 (P)	2.72	2713	0.098	540-570	1000-1060	29	0.28	18.9	10.5	20.9	11.6
354.0	F (P)	2.71	2713	0.098	540-600	1000-1110	32	0.30	20.9	11.6	22.9	12.7
355.0	T51 (S)	2.71	2713	0.098	550-620	1020-1150	43	0.40	22.3	12.4	24.7	13.7
	T6 (S)	2.71	2713	0.098	550-620	1020-1150	36	0.34	22.3	12.4	24.7	13.7
	T61 (S)	2.71	2713	0.098	550-620	1020-1150	37	0.35	22.3	12.4	24.7	13.7
	T7 (S)	2.71	2713	0.098	550-620	1020-1150	42	0.39	22.3	12.4	24.7	13.7
	T6 (P)	2.71	2713	0.098	550-620	1020-1150	39	0.36	22.3	12.4	24.7	13.7
C355.0	T61 (S)	2.71	2713	0.098	550-620	1020-1150	39	0.35	22.3	12.4	24.7	13.7
356.0	T51 (S)	2.68	2685	0.097	560-615	1040-1140	43	0.40	21.4	11.9	23.4	13.0
	T6 (S)	2.68	2685	0.097	560-615	1040-1140	39	0.36	21.4	11.9	23.4	13.0
	T7 (S)	2.68	2685	0.097	560-615	1040-1140	40	0.37	21.4	11.9	23.4	13.0
	T6 (P)	2.68	2685	0.097	560-615	1040-1140	41	0.37	21.4	11.9	23.4	13.0
A356.0	T6 (S)	2.69	2713	0.098	560-610	1040-1130	40	0.36	21.4	11.9	23.4	13.0
357.0	T6 (S)	2.68	2713	0.098	560-615	1040-1140	39	0.36	21.4	11.9	23.4	13.0

A357.0	T6 (S)	2.69	2713	0.098	555-610	1030-1130	40	0.38	21.4	11.9	23.6	13.1
358.0	T6 (S)	2.68	2658	0.096	560-600	1040-1110	39	0.36	21.4	11.9	23.4	13.0
359.0	T6 (S)	2.67	2685	0.097	565-600	1050-1110	35	0.33	20.9	11.6	22.9	12.7
360.0	F (D)	2.68	2685	0.097	570-590	1060-1090	37	0.35	20.9	11.6	22.9	12.7
A360.0	F (D)	2.68	2685	0.097	570-590	1060-1090	37	0.35	21.1	11.7	22.9	12.7
364.0	F (D)	2.63	2630	0.095	560-600	1040-1110	30	0.29	20.9	11.6	22.9	12.7
380.0	F (D)	2.76	2740	0.099	520-590	970-1090	27	0.26	21.2	11.8	22.5	12.5
A380.0	F (D)	2.76	2740	0.099	520-590	970-1090	27	0.26	21.1	11.7	22.7	12.6
384.0	F (D)	2.70	2713	0.098	480-580	900-1080	23	0.23	20.3	11.3	22.1	12.3
390.0	F (D)	2.73	2740	0.099	510-650	950-1200	25	0.32	18.5	10.3	. . .	. . .
	T5 (D)	2.73	2740	0.099	510-650	950-1200	24	0.32	18.0	10.0	. . .	. . .
392.0	F (P)	2.64	2630	0.095	550-670	1020-1240	22	0.22	18.5	10.3	20.2	11.2
413.0	F (D)	2.66	2657	0.096	575-585	1070-1090	39	0.37	20.5	11.4	22.5	12.5
A413.0	F (D)	2.66	2657	0.096	575-585	1070-1090	39	0.37	. . .	. . .	. . .	. . .
443.0	F (S)	2.69	2685	0.097	575-630	1070-1170	37	0.35	22.1	12.3	24.1	13.4
	O (S)	2.69	2685	0.097	575-630	1070-1170	42	0.39	. . .	. . .	. . .	. . .

	F (D)	2.69	2685	0.097	575-630	1070-1170	37	0.34	. . .	. . .	. . .	. . .
A444.0	F (P)	2.68	2685	0.097	575-630	1070-1170	41	0.38	21.8	12.1	23.8	13.2
511.0	F (S)	2.66	2657	0.096	590-640	1090-1180	36	0.34	23.6	13.1	25.7	14.3
512.0	F (S)	2.65	2657	0.096	590-630	1090-1170	38	0.35	22.9	12.7	24.8	13.8
513.0	F (P)	2.68	2685	0.097	580-640	1080-1180	34	0.32	23.9	13.3	25.9	14.4
514.0	F (S)	2.65	2657	0.096	600-640	1110-1180	35	0.33	23.9	13.3	25.9	14.4
518.0	F (D)	2.53	2519	0.091	540-620	1000-1150	24	0.24	24.1	13.4	26.1	14.5
520.0	T4 (S)	2.57	2574	0.093	450-600	840-1110	21	0.21	25.2	14.0	27.0	15.0
535.0	F (S)	2.62	2519	0.091	550-630	1020-1170	23	0.24	23.6	13.1	26.5	14.7
A535.0	F (D)	2.54	2547	0.092	550-620	1020-1150	23	0.24	24.1	13.4	26.1	14.5
B535.0	F (S)	2.62	2630	0.095	550-630	1020-1170	24	0.23	24.5	13.6	26.5	14.7
705.0	F (S)	2.76	2768	0.100	600-640	1110-1180	25	0.25	23.6	13.1	25.7	14.3
707.0	F (S)	2.77	2768	0.100	585-630	1090-1170	25	0.25	23.8	13.2	25.9	14.4
710.0	F (S)	2.81	2823	0.102	600-650	1110-1200	35	0.33	24.1	13.4	26.3	14.6
711.0	F (P)	2.84	2851	0.103	600-645	1110-1190	40	0.38	23.6	13.1	25.6	14.2
712.0	F (S)	2.82	2823	0.102	600-640	1110-1180	40	0.38	23.6	13.1	25.6	14.2

713.0	F (S)	2.84	2879	0.104	595-630	1100-1170	37	0.37	23.9	13.3	25.9	14.4
850.0	T5 (S)	2.87	2851	0.103	225-650	440-1200	47	0.44	. . .	. . .	. . .	. . .
851.0	T5 (S)	2.83	2823	0.102	230-630	450-1170	43	0.40	22.7	12.6	. . .	. . .
852.0	T5 (S)	2.88	2879	0.104	210-635	410-1180	45	0.42	23.2	12.9	. . .	. . .

cgs, centimeter-gram-second.

(a) S = sand cast; P = permanent mold; D = die cast.

(b) The specific gravity and density data in this table assume solid (void-free) metal. Because some porosity cannot be avoided in commercial castings, their specific gravities and densities are slightly less than the theoretical values.

Table 2 Ratings of castability, corrosion resistance, machinability, and weldability for aluminum casting alloys

Alloy	Resistance to hot cracking(a)	Pressure tightness	Fluidity(b)	Shrinkage tendency(c)	Corrosion resistance(d)	Machinability(e)	Weldability(f)
Sand casting alloys							
201.0	4	3	3	4	4	1	2
208.0	2	2	2	2	4	3	3
213.0	3	3	2	3	4	2	2
222.0	4	4	3	4	4	1	3
240.0	4	4	3	4	4	3	4
242.0	4	3	4	4	4	2	3
A242.0	4	4	3	4	4	2	3
295.0	4	4	4	3	3	2	2
319.0	2	2	2	2	3	3	2

354.0	1	1	1	1	3	3	2
355.0	1	1	1	1	3	3	2
A356.0	1	1	1	1	2	3	2
357.0	1	1	1	1	2	3	2
359.0	1	1	1	1	2	3	1
A390.0	3	3	3	3	2	4	2
A443.0	1	1	1	1	2	4	4
444.0	1	1	1	1	2	4	1
511.0	4	5	4	5	1	1	4
512.0	3	4	4	4	1	2	4
514.0	4	5	4	5	1	1	4
520.0	2	5	4	5	1	1	5
535.0	4	5	4	5	1	1	3
A535.0	4	5	4	4	1	1	4
B535.0	4	5	4	4	1	1	4
705.0	5	4	4	4	2	1	4
707.0	5	4	4	4	2	1	4
710.0	5	3	4	4	2	1	4
711.0	5	4	5	4	3	1	3
712.0	4	4	3	3	3	1	4
713.0	4	4	3	4	2	1	3

771.0	4	4	3	3	2	1	. . .
772.0	4	4	3	3	2	1	. . .
850.0	4	4	4	4	3	1	4
851.0	4	4	4	4	3	1	4
852.0	4	4	4	4	3	1	4
Permanent mold casting alloys							
201.0	4	3	3	4	4	1	2
213.0	3	3	2	3	4	2	2
222.0	4	4	3	4	4	1	3
238.0	2	3	2	2	4	2	3
240.0	4	4	3	4	4	3	4
296.0	4	3	4	3	4	3	4
308.0	2	2	2	2	4	3	3
319.0	2	2	2	2	3	3	2
332.0	1	2	1	2	3	4	2
333.0	1	1	2	2	3	3	3
336.0	1	2	2	3	3	4	2
354.0	1	1	1	1	3	3	2
355.0	1	1	1	2	3	3	2
C355.0	1	1	1	2	3	3	2
356.0	1	1	1	1	2	3	2

A356.0	1	1	1	1	2	3	2
357.0	1	1	1	1	2	3	2
A357.0	1	1	1	1	2	3	2
359.0	1	1	1	1	2	3	1
A390.0	2	2	2	3	2	4	2
443.0	1	1	2	1	2	5	1
A444.0	1	1	1	1	2	3	1
512.0	3	4	4	4	1	2	4
513.0	4	5	4	4	1	1	5
711.0	5	4	5	4	3	1	3
771.0	4	4	3	3	2	1	. . .
772.0	4	4	3	3	2	1	. . .
850.0	4	4	4	4	3	1	4
851.0	4	4	4	4	3	1	4
852.0	4	4	4	4	3	1	4
Die casting alloys							
360.0	1	1	2	2	3	4	. . .
A360.0	1	1	2	2	3	4	. . .
364.0	2	2	1	3	4	3	. . .
380.0	2	1	2	5	3	4	. . .
A380.0	2	2	2	4	3	4	. . .

384.0	2	2	1	3	3	4	. . .
390.0	2	2	2	2	4	2	. . .
413.0	1	2	1	2	4	4	. . .
C443.0	2	3	3	2	5	4	. . .
515.0	4	5	5	1	2	4	. . .
518.0	5	5	5	1	1	4	. . .

1, best; 5, worst. Individual alloys may have different ratings for other casting processes.

(a) Ability of alloy to withstand stresses from contraction while cooling through hot short or brittle temperature range.

(b) Ability of liquid alloy to flow readily in mold and to fill thin sections.

(c) Decrease in volume accompanying freezing of alloy and a measure of amount of compensating feed metal required in the form of risers.

(d) Based on resistance of alloy in standard salt spray test.

(e) Composite rating based on ease of cutting, chip characteristics, quality of finish, and tool life.

(f) Based on ability of material to be fusion welded with filler rod of the same alloy.

Table 3 Typical mechanical properties of aluminum sand casting alloys based on tests of separately cast specimens

Aluminum Association No.	Temper	Tensile strength		Tensile yield strength(a)		Elongation in 50 mm or 2 in., %	Hardness(b), HB	Compressive yield strength(a)		Shear strength		Endurance limit(c)		Modulus of elasticity(d)	
		MPa	**ksi**	**MPa**	**ksi**			**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**GPa**	**10^6 psi**
201.0	T43	414	60	255	37	17.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T6	448	65	379	55	8.0	130	386	56	290	42	. . .	. . .	. . .	. . .
	T7	467	68	414	60	5.5	. . .	. . .	. . .	. . .	. . .	97	14	. . .	. . .

A206.0	T4	354	51	250	36	7.0	. . .	264	38	278	40	. . .	. . .	. . .	. . .
208.0	F	145	21	97	14	2.5	55	103	15	117	17	76	11	. . .	. . .
213.0	F	165	24	103	15	1.5	70	110	16	138	20	62	9	. . .	. . .
222.0	O	186	27	138	20	1.0	80	138	20	145	21	65	9.5	. . .	. . .
	T61	283	41	276	40	<0.5	115	296	43	221	32	59	8.5	74	10.7
	T62	421	61	331	48	4.0	. . .	338	49	262	38	. . .	. . .	. . .	. . .
224.0	T72	380	55	276	40	10.0	123	283	41	245	36	62	9.0	72	10.5
240.0	F	235	34	200	29	1.0	90	207	30	. . .	. . .	. . .	. . .	. . .	. . .
242.0	F	214	31	217	31	0.5	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	O	186	27	124	18	1.0	70	124	18	145	21	55	8	71	10.3
	T571	221	32	207	30	0.5	85	234	34	179	26	76	11	71	10.3
	T77	207	30	159	23	2.0	75	165	24	165	24	72	10.5	71	10.3
A242.0	T75	214	31	. . .	. . .	2.0	. . .	483	70	. . .	. . .	. . .	. . .	. . .	. . .
295.0	T4(e)	221	32	110	16	8.5	60	117	17	179	26	48	7	69	10.0
	T6	250	36	165	24	5.0	75	172	25	217	31	52	7.5	69	10.0
	T62	283	41	221	32	2.0	90	234	34	228	33	55	8	69	10.0
319.0	F	186	27	124	18	2.0	70	131	19	152	22	69	10	74	10.7
	T5	207	30	179	26	1.5	80	186	27	164	24	76	11	75	10.7
	T6	250	36	164	24	2.0	80	172	25	200	29	76	11	74	10.7
355.0	F	159	23	83	12	3.0	. . .	. . .	. . .	. . .	. .	. . .	. . .	. . .	. . .

										.					
	T51	193	28	159	23	1.5	65	164	24	152	22	55	8	70	10.2
	T6	241	35	172	25	3.0	80	179	26	193	28	62	9	70	10.2
	T61	269	39	241	35	1.0	90	255	37	214	31	65	9.5	. . .	. . .
	T7	264	38	250	36	0.5	85	264	38	193	28	69	10	70	10.2
	T71	241	35	200	29	1.5	75	207	30	179	26	69	10	70	10.2
C355.0	T6	269	39	200	29	5.0	85	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
356.0	F	164	24	124	18	6.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T51	172	25	138	20	2.0	60	145	21	138	20	55	8	72	10.5
	T6	228	33	164	24	3.5	70	172	25	179	26	59	8.5	72	10.5
	T7	234	34	207	30	2.0	75	214	31	164	24	62	9	72	10.5
	T71	193	28	145	21	3.5	60	152	22	138	20	59	8.5	72	10.5
A356.0	F	159	23	83	12	6.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T51	179	26	124	18	3.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T6	278	40	207	30	6.0	75	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T71	207	30	138	20	3.5	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
357.0	F	172	25	90	13	5.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T51	179	26	117	17	3.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

	T6	345	50	296	43	2.0	90	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T7	278	40	234	34	3.0	60	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
A357.0	T6	317	46	248	36	3.0	85	241	35	278	40	83	12	. . .	. . .
A390.0	F	179	26	179	26	<1.0	100	. . .	. . .	. . .	. . .	. . .	. . .	82	11.9
	T5	179	26	179	26	<1.0	100	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T6	278	40	278	40	<1.0	140	. . .	. . .	. . .	. . .	90	13	. . .	. . .
	T7	250	36	250	36	<1.0	115	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
443.0	F	131	19	55	8	8.0	40	62	9	97	14	55	8	71	10.2
A444.0	F	145	21	62	9	9.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T4	159	23	62	9	12.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
511.0	F	145	21	83	12	3.0	50	90	13	117	17	55	8	. . .	. . .
512.0	F	138	20	90	13	2.0	50	97	14	117	17	59	8.5	. . .	. . .
514.0	F	172	25	83	12	9.0	50	83	12	138	20	48	7	71	10.2
520.0	T4	331	48	179	26	16.0	75	186	27	234	34	55	8	65	9.5
A535.0	F	250	36	124	18	9.0	65	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
710.0	F	241	35(f)	172	25(f)	5.0(f)	75(f)	172	25	179	26	55	8	67	9.7
712.0(h)	F	241	35	172	25	5.0	75	172	25	179	26	62	9	. . .	. . .
713.0(h)	F	241	35	172	25	5.0	74	. . .	. . .	. . .	. . .	. . .	. . .	67	9.7

850.0	T5	138	20	76	11	8.0	45	76	11	97	14	. . .	. . .	71	10.2
851.0	T5	138	20	76	11	5.0	45	76	11	97	14	. . .	. . .	71	10.2
852.0	T5	186	27	152	22	2.0	65	152	22	124	18	69	10	71	10.2

Tensile and hardness values determined by tests on standard 13 mm ($\frac{1}{2}$ in.) diam test specimens, without surface machining, each cast in a green sand mold.

(a) Offset; 0.2%.

(b) 500 kg (1102 lb) load on 10 mm (0.4 in.) ball.

(c) Endurance limits based on 500 million cycles of completely reversed stresses using rotating beam-type machine and specimen.

(d) Average tension and compression moduli, compression modulus is ~2% greater than tension modulus.

(e) Properties of T4 approach those of T6 after standing for several weeks at room temperature.

(f) Tests completed approximately 30 days after casting.

(g) (g) Tests completed ten days after casting.

Table 4 Typical mechanical properties of aluminum permanent mold casting alloys based on tests of separately cast specimens

Aluminum Association No.	Temper	Tensile strength		Tensile yield strength[a]		Elongation in 50 mm or 2 in., %	Hardness[b], HB	Compressive yield strength[a]		Shear strength		Endurance limit[c]		Modulus of elasticity[d]	
		MPa	**ksi**	**MPa**	**ksi**			**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**GPa**	**10^6 psi**
201.0	T43	414	60	255	37	17.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T6	448	65	379	55	8.0	130	386	56	290	42	. . .	. . .	. . .	. . .
	T7	469	68	414	60	5.0	. . .	. . .	. . .	. . .	. . .	97	14	. . .	. . .
A206.0	T4	431	62	264	38	17.0	. . .	285	41	292	42	. . .	. . .	. . .	. . .

	T7	436	63	347	50	11.7	. . .	372	54	257	37	. . .	. . .	. . .	. . .
213.0	F	207	30	165	24	1.5	85	172	25	165	24	66	9.5	. . .	. . .
222.0	T52	241	35	214	31	1.0	100	214	31	172	25	. . .	. . .	. . .	. . .
	T551	255	37	241	35	<0.5	115	276	40	207	30	59	8.5	74	10.7
	T65	331	48	248	36	<0.5	140	248	36	248	26	62	9	74	10.7
238.0	F	207	30	165	24	1.5	100	207	30	165	24	. . .	. . .	. . .	. . .
242.0	T571	276	40	234	34	1.0	105	234	34	207	30	72	10.5	71	10.3
	T61	324	47	290	42	0.5	110	303	44	241	35	66	9.5	71	10.3
249.0	T63	476	69	414	60	6.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T7	278	62	359	52	9.0	. . .	414	60	276	40	55	8.0	72	10.5
296.0	T4(e)	255	37	131	19	9.0	75	138	20	207	30	66	9.5	70	10.1
	T6	276	40	179	26	5.0	90	179	26	221	32	69	10	70	10.1
	T7	270	39	138	20	4.5	80	138	20	207	30	63	9	70	10.1
308.0	F	193	28	110	16	2.0	70	117	17	152	22	90	13	. . .	. . .
319.0	F	234	34	131	19	2.5	85	131	19	165	24	. . .	. . .	. . .	. . .
	T6	276	40	186	27	3.0	95	186	27	. . .	. . .	. . .	. . .	. . .	. . .
324.0	F	207	30	110	16	4.0	70	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T5	248	36	179	26	3.0	90	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T62	310	45	269	39	3.0	105	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

332.0	T5	248	36	193	28	1.0	105	. . .	. . .	. . .	. . .	. . .	. . .	77	11.2
333.0	F	234	34	131	19	2.0	90	131	19	186	27	100	14.5	. . .	. . .
	T5	234	34	172	25	1.0	100	172	25	186	27	83	12	. . .	. . .
	T6	290	42	207	30	1.5	105	207	30	228	33	103	15	. . .	. . .
	T7	255	37	193	28	2.0	90	193	28	193	28	83	12	. . .	. . .
336.0	T551	248	36	193	28	0.5	105	193	28	193	28	93	13.5	. . .	. . .
	T65	324	47	296	43	0.5	125	296	43	248	36	. . .	. . .	. . .	. . .
355.0	T51	205	30	165	24	2.0	75	165	24	165	24	. . .	. . .	. . .	. . .
	T6	290	42	185	27	4.0	90	185	27	235	34	69	10	. . .	. . .
	T61	310	45	275	40	1.5	105	275	40	250	36	69	10	. . .	. . .
	T7	275	40	205	30	2.0	85	205	30	205	30	69	10	. . .	. . .
	T71	250	36	215	31	3.0	85	215	31	185	27	69	10	. . .	. . .
C355.0	T61	303	44	234	34	3.0	90	248	36	221	32	97	14	. . .	. . .
356.0	F	179	26	124	18	5.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	
	T51	186	27	138	20	2.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	
	T6	262	38	186	27	5.0	80	186	27	207	30	90	13	72	10.5
	T7	221	32	165	24	6.0	70	165	24	172	25	76	11	72	10.5
A356.0	T61	283	41	207	30	10.0	90	221	32	193	28	90	13	72	10.5
357.0	F	193	28	103	15	6.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	

	T51	200	29	145	21	4.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	
	T6	359	52	296	43	5.0	100	303	44	241	35	90	13	. . .	. . .
A357.0	T6	359	52	290	42	5.0	100	296	43	241	35	103	15	. . .	. . .
359.0	T62	345	50	290	42	5.5	. . .	. . .	. . .	. . .	. . .	110	16	. . .	. . .
A390.0	F	200	29	200	29	<1.0	110	. . .	. . .	. . .	. . .	. . .	. . .	82	11.9
	T5	200	29	200	29	<1.0	110	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T6	310	45	310	45	<1.0	145	414	60	. . .	. . .	117	17	. . .	. . .
	T7	262	38	262	38	<1.0	120	359	52	. . .	. . .	100	14.5	. . .	. . .
443.0	F	159	23	62	9	10.0	45	62	9	110	16	55	8	71	10.3
A444.0	F	165	24	76	11	13.0	44	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
	T4	159	23	69	10	21.0	45	76	11	110	16	55	8	. . .	. . .
513.0	F	186	27	110	16	7.0	60	117	17	152	22	69	10	. . .	. . .
711.0	F	241	35(f)	124	18(f)	8.0(f)	70(f)	. . .	. . .	. . .	. . .	76	11	76	11.0
850.0	T5	159	23	76	11	12.0	45	76	11	103	15	62	9	71	10.3
851.0	T5	138	20	76	11	5.0	45	76	11	97	14	62	9	71	10.3
852.0	T5	221	32	159	23	5.0	70	159	23	148	21	76	11	71	10.3

Tension and hardness values determined by tests on standard 13 mm ($\frac{1}{2}$ in.) diam test specimens, without surface machining, each cast in permanent mold.

(a) At 0.2% offset.

(b) 500 kg (1102 lb) load on 10 mm (0.4 in.) ball.

(c) Endurance limits based on 500 million cycles of completely reversed stresses using rotating beam-type machine and specimen.

(d) Average of tension and compression moduli; compression modulus is ~2% greater than tension modulus.

(e) Properties of T4 approach those of T6 after standing for several weeks at room temperature.

(f) Tests made approximately 30 days after casting.

Table 5 Typical mechanical properties of aluminum die casting alloys based on tests of separately cast specimens

Aluminum Association No.	Temper	Tensile strength		Yield strength[a]		Elongation in 50 mm or 2 in., %	Hardness[b], HB	Shear strength		Endurance limit[c]		Modulus of elasticity[d]	
		MPa	**ksi**	**MPa**	**ksi**			**MPa**	**ksi**	**MPa**	**ksi**	**GPa**	**10^6 psi**
360.0	F	324	47	172	25	3.0	75	207	30	131	19	71	10.3
A360.0	F	317	46	165	24	5.0	75	200	29	124	18	. . .	. . .
364.0	F	296	43	159	23	7.5	. . .	179	26	124	18	. . .	. . .
380.0	F	331	48	165	24	3.0	80	214	31	145	21	71	10.3
A380.0	F	324	47	159	23	4.0	80	207	30	138	20	. . .	. . .
384.0	F	324	47	172	25	1.0	. . .	207	30	145	21	71	10.3
390.0	F	279	40.5	241	35	1.0	120	. . .	. . .	138	20	82	11.9
	T5	296	43	265	38.5	1.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .
392.0	F	290	42	262	38	<0.5	. . .	234[e]	34[e]	103[e]	15[e]	. . .	. . .
413.0	F	296	43	145	21	2.5	80	193	28	131	19	71	10.3
A413.0	F	241	35	110	16	3.5	80	172	25	131	19	. . .	. . .
443.0	F	228	33	110	16	9.0	50	145	21	117	17	71	10.3

513.0	F	276	40	152	22	10.0	. . .	179	26	124	18	. . .	. . .
515.0	F	283	41	. . .	. . .	10.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .
518.0	F	310	45	186	27	8.0	80	200	29	138	20	. . .	. . .

Tension properties are average values determined from ASTM standard 6 mm ($\frac{1}{4}$ in.) diam test specimens cast on a cold chamber (high-pressure) die casting machine.

(a) At 0.2% offset.

(b) 500 kg (1102 lb) load on 10 mm (0.4 in.) ball.

(c) Endurance limits based on 500 million cycles of completely reversed stresses using rotating beam-type machine and specimen.

(d) Average of tension and compression moduli; compression modulus is ∼2% greater than tension modulus.

(e) Estimated

Table 6 Mechanical-property limits for aluminum sand casting alloys

Aluminum Association No.	Temper	Minimum properties[(a)]				
		Tensile strength		**Yield strength**		**Elongation in 50 mm or 2 in., %**
		MPa	**ksi**	**MPa**	**ksi**	
201.0	T6	414	60.0	345	50.0	5.0
	T7	414	60.0	345	50.0	3.0
204.0	T4	310	45.0	193	28.0	6.0
208.0	F	131	19.0	83	12.0	1.5
	T55	145	21.0	. . .	. . .	. . .
222.0	O	159	23.0	. . .	. . .	. . .
	T61	207	30.0	. . .	. . .	. . .

242.0	O	159	23.0	. . .	. . .	. . .
	T571	200	29.0	. . .	. . .	. . .
	T61	221	32.0	138	20.0	. . .
	T77	165	24.0	90	13.0	1.0
295.0	T4	200	29.0	90	13.0	6.0
	T6	221	32.0	138	20.0	3.0
	T62	248	36.0	193	28.0	. . .
	T7	200	29.0	110	16.0	3.0
319.0	F	159	23.0	90	13.0	1.5
	T5	172	25.0	. . .	. . .	. . .
	T6	214	31.0	138	20.0	1.5
328.0	F	172	25.0	97	14.0	1.0
	T6	234	34.0	145	21.0	1.0
354.0	(b)	. . .	. . .	. . .	. . .	. . .
355.0	T51	172	25.0	124	18.0	. . .
	T6	221	32.0	138	20.0	2.0
	T7	241	35.0	. . .	. . .	. . .
	T71	207	30.0	152	22.0	. . .
C355.0	T6	248	36.0	172	25.0	2.5
356.0	F	131	19.0	. . .	. . .	2.0
	T51	159	23.0	110	16.0	. . .

	T6	207	30.0	138	20.0	3.0
	T7	214	31.0	200	29.0	. . .
	T71	172	25.0	124	18.0	3.0
A356.0	T6	234	34.0	165	24.0	3.5
A357.0	(b)	. . .	. . .	. . .	. . .	. . .
359.0	(b)	. . .	. . .	. . .	. . .	. . .
443.0	F	117	17.0	48	7.0	3.0
B443.0	F	117	17.0	41	6.0	3.0
514.0	F	152	22.0	62	9.0	6.0
520.0	T4	290	42.0	152	22.0	12.0
535.0	F or T5	241	35.0	124	18.0	9.0
705.0	F or T5	207	30.0	117	17.0	5.0
707.0	F or T5	227	33.0	152	22.0	2.0
	T7	255	37.0	207	30.0	1.0
710.0	F or T5	221	32.0	138	20.0	2.0
712.0	F or T5	234	34.0	172	25.0	4.0
713.0	F or T5	221	32.0	152	22.0	3.0
771.0	T5	290	42.0	262	38.0	1.5
	T51	221	32.0	186	27.0	3.0
	T52	248	36.0	207	30.0	1.5
	T53	248	36.0	186	27.0	1.5

	T6	290	42.0	241	35.0	5.0
	T71	331	48.0	310	45.0	2.0
850.0	T5	110	16.0	. . .	. . .	5.0
851.0	T5	117	17.0	. . .	. . .	3.0
852.0	T5	165	24.0	124	18.0	. . .

(a) These values represent properties obtained from separately cast test bars and are derived from ASTM B 26, Standard Specification for Aluminum Alloy Sand Castings; Federal Specification QQ-A-601e, Aluminum Alloy Sand Castings; and Military Specification MIL-A-21180C, Aluminum Alloy Castings, High Strength. Unless otherwise specified, the average values of tensile strength, yield strength, and elongation for specimens cut from castings should not be less than 75% of the tensile and yield strength values, and not less than 25% of the elongation values, given above. The customer should keep in mind that some foundries may offer additional tempers for the above alloys and that foundries are constantly improving casting techniques and, as a result, may offer minimum properties in excess of those given here.

(b) Mechanical properties of this alloy depend on the casting process. For further information, consult the individual foundries.

Table 7 Mechanical-property limits for aluminum permanent mold casting alloys

Aluminum Association No.	Temper	Minimum properties[(a)]				
		Tensile strength		**Yield strength**		**Elongation in 50 mm or 2 in., %**
		MPa	**ksi**	**MPa**	**ksi**	
204.0	T4	331	48.0	200	29.0	8.0
208.0	T4	227	33.0	103	15.0	4.5
	T6	241	35.0	152	22.0	2.0
	T7	227	33.0	110	16.0	3.0
213.0	F	159	23.0	. . .	. . .	. . .
222.0	T551	207	30.0	. . .	. . .	. . .
	T65	276	40.0	. . .	. . .	. . .
242.0	T571	234	34.0	. . .	. . .	. . .

	T61	276	40.0	. . .	. . .	. . .
296.0	T4	227	33.0	. . .	. . .	4.5
	T6	241	35.0	. . .	. . .	2.0
	T7	227	33.0	. . .	. . .	3.0
308.0	F	165	24.0	. . .	. . .	. . .
319.0	F	193	28.0	97	14.0	1.5
	T6	234	34.0	. . .	. . .	2.0
332.0	T5	214	31.0	. . .	. . .	. . .
333.0	F	193	28.0	. . .	. . .	. . .
	T5	207	30.0	. . .	. . .	. . .
	T6	241	35.0	. . .	. . .	. . .
	T7	214	31.0	. . .	. . .	. . .
336.0	T551	214	31.0	. . .	. . .	. . .
	T65	276	40.0	. . .	. . .	. . .
354.0	(b)	. . .	. . .	. . .	. . .	. . .
355.0	T51	186	27.0	. . .	. . .	. . .
	T6	255	37.0	. . .	. . .	1.5
	T62	290	42.0	. . .	. . .	. . .
	T7	248	36.0	. . .	. . .	. . .
	T71	234	34.0	186	27.0	. . .
C355.0	T61	276	40.0	207	30.0	3.0

356.0	F	145	21.0	. . .	. . .	3.0
	T51	172	25.0	. . .	. . .	. . .
	T6	227	33.0	152	22.0	3.0
	T7	172	25.0	. . .	. . .	3.0
	T71	172	25.0	. . .	. . .	3.0
A356.0	T61	255	37.0	179	26.0	5.0
357.0	T6	310	45.0	. . .	. . .	3.0
A357.0	(b)	. . .	. . .	. . .	. . .	. . .
359.0	(b)	. . .	. . .	. . .	. . .	. . .
443.0	F	145	21.0	48	7.0	2.0
B443.0	F	145	21.0	41	6.0	2.5
A444.0	T4	138	20.0	. . .	. . .	20.0
513.0	F	152	22.0	83	12.0	2.5
535.0	F	241	35.0	124	18.0	8.0
705.0	T5	255	37.0	117	17.0	10.0
707.0	T5	290	42.0	172	25.0	4.0
	T7	310	45.0	241	35.0	3.0
711.0	T1	193	28.0	124	18.0	7.0
713.0	T5	221	32.0	152	22.0	4.0
850.0	T5	124	18.0	. . .	. . .	8.0
851.0	T5	117	17.0	. . .	. . .	3.0

	T6	124	18.0	. . .	. . .	8.0
852.0	T5	186	27.0	. . .	. . .	3.0

(a) These values represent properties obtained from separately cast test bars and are derived from ASTM B 108, Standard Specification for Aluminum Alloy Permanent Mold Castings; Federal Specification QQ-A596d, Aluminum Alloy Permanent and Semipermanent Mold Castings; and Military Specification MIL-A-21180c, Aluminum Alloy Castings, High Strength. Unless otherwise specified, the average values of tensile strength, yield strength, and elongation for specimens cut from castings should not be less than 75% of the tensile and yield strength values and not <25% of the elongation values, given above. The customer should keep in mind that some foundries may offer additional tempers for the above alloys and that foundries are constantly improving casting techniques and, as a result, may offer minimum properties in excess of those given here.

(b) Mechanical properties of this alloy depend on the casting process. For further information, consult the individual foundries.

Table 8 Mechanical-property limits (when specified) for specimens cut from aluminum alloy permanent mold castings (from ASTM B 108)

Alloy and temper	Minimum properties				
	Tensile strength		**Yield strength**		**Elongation, %**
	MPa	**ksi**	**MPa**	**ksi**	
Specimens cut from designated areas of castings					
354.0-T61	324	47	248	36	3.0
354.0-T62	344	50	290	42	2.0
C355.0-T61	276	40	207	30	3.0
A356.0-T61	228	33	179	26	5.0
A357.0-T61	317	46	248	36	3.0
359.0-T61	310	45	234	34	4.0
359.0-T62	324	47	262	38	3.0
A444.0-T4	138	20	. . .	. . .	20.0
Specimens cut from any location in castings					

354.0-T61, -T62	297	43	228	33	2.0
C355.0-T61	255	37	207	30	3.0
A356.0-T61	193	28	179	26	3.0
A357.0-T61	283	41	214	31	3.0
359.0-T61, -T62	276	40	207	30	3.0
A444.0-T4	138	20	. . .	. . .	20.0

Table 9 Typical mechanical properties of premium-quality aluminum alloy castings and elevated-temperature aluminum casting alloys

Alloy and temper	Hardness HB[a]	Ultimate tensile strength		Tensile yield strength		Elongation in 50 mm (2 in.), %	Compressive yield strength		Shear strength		Fatigue strength[b]	
		MPa	**ksi**	**MPa**	**ksi**		**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**
Premium-quality castings[c]												
A201.0-T7	. . .	495	72	448	65	6	. . .	. . .	. . .	. . .	97	14
A206.0-T7	. . .	445	65	405	59	6	. . .	. . .	. . .	. . .	90	13
224.0-T7	. . .	420	61	330	48	4	. . .	. . .	. . .	. . .	86	12.5
249.0-T7	. . .	470	68	407	59	6	. . .	. . .	. . .	. . .	75	11
354.0-T6	. . .	380	55	283	41	6	. . .	. . .	. . .	. . .	135[d]	19.5[d]
C355.0-T6	. . .	317	46	235	34	6	. . .	. . .	. . .	. . .	97	14
A356.0-T6	. . .	283	41	207	30	10	. . .	. . .	. . .	. . .	90	13
A357.0-T6	. . .	360	52	290	42	8	. . .	. . .	. . .	. . .	90	13
Piston and elevated-temperature sand cast alloys												
222.0-T2	80	185	27	138	20	1	. . .	. . .	. . .	. . .	. . .	. . .

222.0-T6	115	283	41	275	40	<0.5	. . .	. . .	. . .	. . .	. . .	. . .
242.0-T21	70	185	27	125	18	1	. . .	. . .	145	21	55	8
242.0-T571	85	220	32	207	30	0.5	. . .	. . .	180	26	75	11
242.0-T77	75	207	30	160	23	2	165	24	165	24	72	10.5
A242.0-T75	. . .	215	31	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
243.0	95	207	30	160	23	2	200	29	70	10	70	10
328.0-F	. . .	220	32	130	19	2.5	. . .	. . .	. . .	. . .	. . .	. . .
328.0-T6	85	290	42	185	27	4.0	180	26	193	28	. . .	. . .
Piston and elevated-temperature alloys (permanent mold castings)												
222.0-T55	115	255	37	240	35	. . .	295	43	207	30	59	8.5
222.0-T65	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
242.0-T571	105	275	40	235	34	1	. . .	. . .	207	30	72	10.5
242.0-T61	110	325	47	290	42	0.5	. . .	. . .	240	35	65	9.5
332.0-T551	105	248	36	193	28	0.5	193	28	193	28	90	13
332.0-T5	105	248	36	193	28	1	200	29	193	28	90	13
336.0-T65	125	325	47	295	43	0.5	193	28	248	36	. . .	. . .
336.0-T551	105	248	36	193	28	0.5	193	28	193	28	. . .	. . .

(a) 10 mm (0.4 in.) ball with 500 kgf (1100 lbf) load.

(b) Rotating beam test at 5 × 10^8 cycles.

(c) Typical values of premium-quality casting are the same regardless of class or the area from which the specimen is cut; see Table 10 for minimum values.

(d) Fatigue strength for 10^6 cycles

Table 10 Minimum tensile properties of premium-quality aluminum alloy castings

Alloy	Class	Ultimate tensile strength (min)		0.2% offset yield strength (min)		Elongation in 50 mm (2 in.), %
		MPa	**ksi**	**MPa**	**ksi**	
Specimens cut from designated casting areas						
A201.0-T7[(a)]	Class 1	414	60	345	50	5
	Class 2	414	60	345	50	3
224.0-T7	Class 1	345	50	255	37	3
	Class 2	379	55	255	37	5
249.0-T7	Class 1	345	50	276	40	2
	Class 2	379	55	310	45	3
	Class 3	414	60	345	50	5
354.0-T6[(a)]	Class 1	324	47	248	36	3
	Class 2	345	50	290	42	2
C355.0-T6[(a)]	Class 1	283	41	214	31	3
	Class 2	303	44	228	33	3
	Class 3	345	50	276	40	2
A356.0-T6[(a)]	Class 1	262	38	193	28	5
	Class 2	276	40	207	30	3
	Class 3	310	45	234	34	3
A357.0-T6[(a)]	Class 1	310	45	241	35	3

	Class 2	345	50	276	40	3
224.0	Class 1	345	50	255	37	3
	Class 2	379	55	255	37	5
Specimens cut from any area						
A201.0-T7[(a)]	Class 10	386	56	331	48	3
	Class 11	379	55	331	48	1.5
224.0-T7	Class 10	310	45	241	35	2
	Class 11	345	50	255	37	3
249.0-T7	Class 10	379	55	310	45	3
	Class 11	345	50	276	40	2
354.0-T6[(a)]	Class 10	324	47	248	36	3
	Class 11	296	43	228	33	2
355.0-T6[(a)]	Class 10	283	41	214	31	3
	Class 11	255	37	207	30	1
	Class 12	241	35	193	28	1
A356.0-T6[(a)]	Class 10	262	38	193	28	5
	Class 11	228	33	186	27	3
	Class 12	221	32	152	22	2
A357.0-T6[(a)]	Class 10	262	38	193	28	5
	Class 11	283	41	214	31	3
224.0	Class 10	310	45	241	35	2

	Class 11	345	50	255	37	3

These mechanical property values are attainable in favorable casting configurations and must be negotiated with the foundry for the particular configuration desired.

(a) Values from specification MIL-A-21180

Table 11 Creep-rupture properties of separately sand cast test bars of alloy 201.0

Temperature		Time under stress(a), h	Rupture stress		Minimum creep rate rupture stress, % per h	Stress for creep of:					
						1.0%		**0.5%**		**0.25%**	
°C	**°F**		**MPa**	**ksi**		**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**
150	300	10	Above yield		. . .	. . .	. . .	. . .	. . .	. . .	. . .
		100	Above yield		. . .	. . .	. . .	. . .	. . .	. . .	. . .
		1,000	270	39	0.00013	260	38	250	36	250	36
		10,000	195	28	0.000023	195	28	185	27	180	76
205	400	10	250	36	0.0145	240	35	230	33	220	32
		100	180	26	0.0024	180	26	170	24	170	24
		1,000	130	19	0.00046	130	19	125	18	110	16
		10,000	95	14	0.000088	95	14	90	13	85	12
260	500	10	140	20	0.047	140	20	125	18	110	16
		100	95	14	0.0080	95	14	95	14	85	12
		1,000	70	10	0.00130	70	10	70	9.8	60	8.6
		10,000	50	7.5	0.00028	50	7.5	50	7.2	45	6.3

(a) 10,000 h data are extrapolated

Table 12 Creep-rupture properties of separately cast test bars of alloy C355.0-T61

Temperature		Time under stress, h	Rupture stress		Stress for creep of:							
					1%		**0.5%**		**0.2%**		**0.1%**	
°C	**°F**		**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**
150	300	0.1	285	41	275	40	270	39	240	35	230	33
		1	285	41	270	39	260	38	235	34	220	32
		10	275	40	260	38	250	36	230	33	205	30
		100	260	38	250	36	235	34	215	31	170	25
		1000	220	32	215	31	206	30	185	27	140	20
205	400	0.1	250	36	250	36	240	35	230	33	170	25
		1	230	33	220	32	205	30	170	25	140	20
		10	180	26	120	25	160	23	130	19	110	16
		100	130	19	130	19	125	18	97	14	. . .	. . .
		1000	97	14	90	13	83	12	. . .	. . .	. . .	. . .
260	500	0.1	165	24	145	21	130	19	105	15	83	12
		1	125	18	110	16	97	14	83	12	59	8.5
		10	90	13	83	12	76	11	59	8.5	41	6
		100	62	9	62	9	55	8	41	6	. . .	. . .
		1000	45	6.5	45	6.5	41	6	. . .	. . .	. . .	. . .

Table 13 Creep-rupture properties of separately cast test bars of alloy A356.0-T61 at 150 °C (300 °F)

Time under stress, h	Rupture stress		Stress for creep of:							
			1%		**0.5%**		**0.2%**		**0.1%**	
	MPa	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**
0.1	235	34	215	31	205	30	195	28	185	27
1	235	34	215	31	200	29	185	27	180	26
10	230	33	205	30	195	28	180	26	170	25
100	200	29	195	28	185	27	170	25	165	24
1000	165	24	165	24	160	23	. . .	. . .	. . .	. . .

Table 14 Fatigue strengths of separately cast test bars of alloy 354.0-T61

Temperature		Fatigue strength at:											
		10^4 cycles		**10^5 cycles**		**10^6 cycles**		**10^7 cycles**		**10^8 cycles**		**5×10^8 cycles**	
°C	**°F**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**
24	75	345	50	275	40	215	31	175	25.5	145	21	135	19.5
150	300	. . .	. . .	255	37	200	29	150	21.5	115	17	110	16
205	400	. . .	. . .	215	31	150	22	105	15	70	10	60	9
260	500	195	28	140	20.5	96	14	60	9	40	6	40	6
315	600	. . .	. . .	75	11	55	8	40	6	30	4	30	4

Table 15 Fatigue properties for separately cast test bars of alloy C355.0-T61

Temperature		Number cycles	Fatigue strength(a)	
°C	**°F**		**MPa**	**ksi**
24	75	10^5	195	28.0
		10^6	130	19.0
		10^7	110	16.0
		10^8	100	14.5
		5×10^8	95	14.0
260	500	10^5	125	18.0
		10^6	80	11.5
		10^7	50	7.5
		10^8	40	5.5
		5×10^8	35	5.0

(a) Based on rotating-beam tests at room temperature and cantilever beam (rotating load) tests at elevated temperature

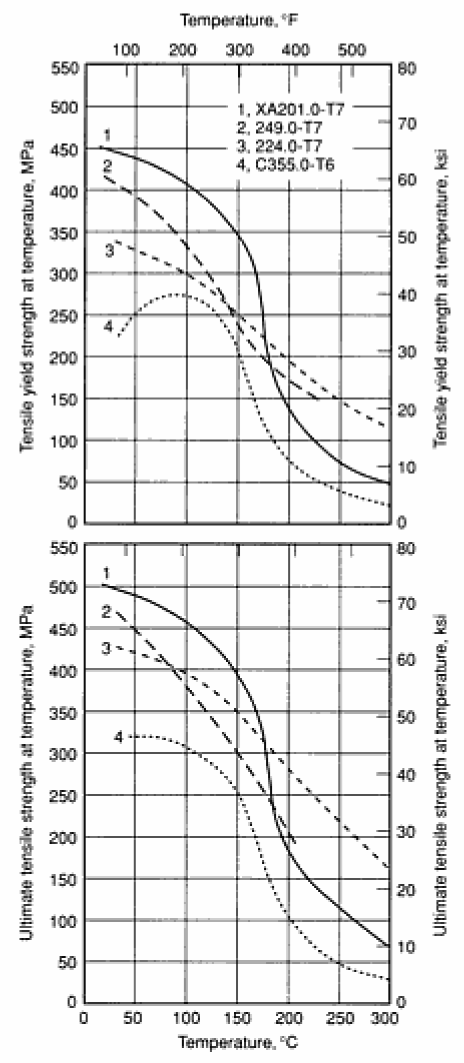


Fig. 1 Elevated-temperature tensile strengths of various premium casting alloys suggested for elevated-temperature service. Duration of temperature exposure was 10,000 h.

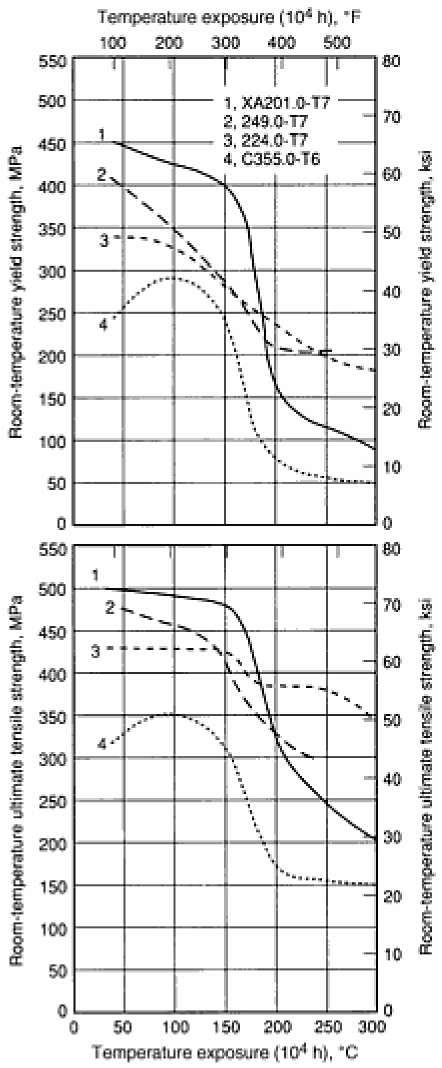


Fig. 2 Room-temperature tensile strengths of various aluminum alloy premium-quality castings after 10,000 h temperature exposure

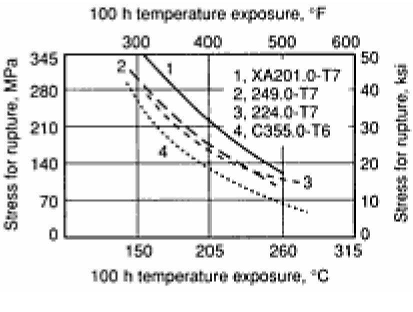


Fig. 3 100 hour stress rupture of premium-quality aluminum alloy castings

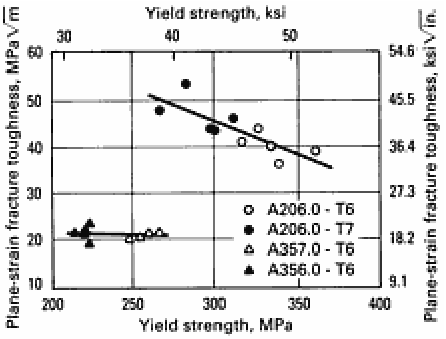


Fig. 4 Variation in plain strain-fracture toughness with yield strength of alloys A206.0, A357.0, and A356.0

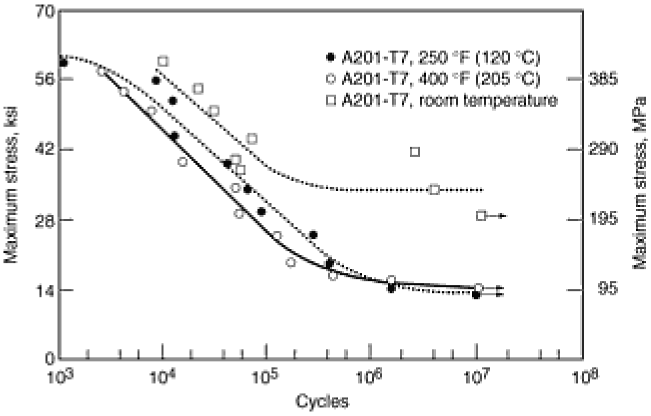


Fig. 5 Stress-life fatigue data at three test temperatures for alloy A201-T7

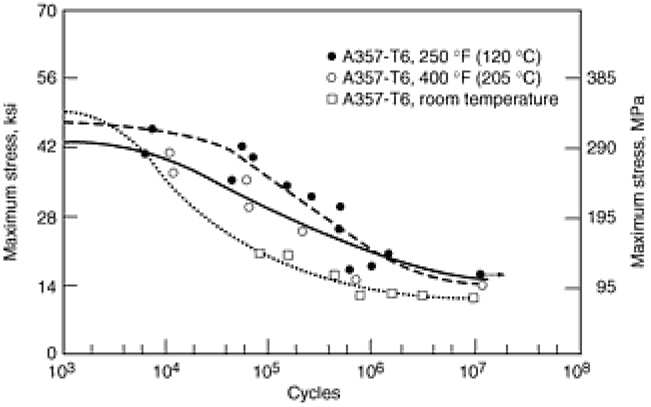


Fig. 6 Stress-life fatigue data at three test temperatures for alloy A357-T6

Aluminum Powder Metallurgy Products

Introduction

ALUMINUM POWDER METALLURGY (P/M) products constitute a very small part of the overall aluminum industry. In fact, the majority of the aluminum powder produced is not used for structural components. Instead, aluminum powders are used in unconsolidated form for use in paints/pigments for roof and automotive coatings; in powder metal-filled plastics; for fuel propellants, pyrotechnics (fireworks), and commercial explosives; metal powder cutting operations (iron-aluminum powders); and thermit welding (aluminothermic compounds). Nevertheless, interest in aluminum P/M alloys for structural applications continues because P/M processing provides much finer and homogeneous microstructures, better mechanical properties, and near-net shape parts producibility for aluminum alloys in comparison with ingot metallurgy (I/M). In addition to the conventional blending and consolidation of elemental or prealloyed powders into near-net shape parts (pressed-and-sintered P/M parts), emerging processes such as mechanical alloying (MA) and rapid solidification (RS) create powders that upon subsequent consolidation provide significant improvements in room- and elevated-temperature strength, fracture toughness, fatigue life, and resistance to corrosion and stress-corrosion cracking (SCC). Another advantage of advanced P/M processing methods, including the spray deposition/forming process, is in the production of new alloys (and composites) with metallurgical structures and compositions that cannot be produced by I/M. Rapid solidification processing extends the solubility of alloying elements, particularly transition and rare earth elements, and refines the structure of intermetallic phases responsible for improved mechanical properties. Mechanical alloying is a dry, high-energy milling process that produces dispersions of insoluble oxides and carbides that stabilize the microstructure leading to high strength at elevated temperature in the consolidated materials.

Despite the advantages of P/M processing for aluminum alloys, their large-scale commercialization has not been realized. Notwithstanding the high cost that remains a major concern for their use, there are other technological challenges such as reproducibility/reliability, machining, joining, and recycling that need to be addressed.

Pressed-and-Sintered P/M Parts

Pressed and sintered alloys consist of aluminum powder admixed with small amounts of copper, magnesium, and silicon (Table 1). Compacts are pressed at 140 to 345 MPa (10 to 25 tsi) and sintered at 595 to 620 °C (1100 to 1150 °F) in nitrogen to 90 to 95% of theoretical density (sintering in dissociated ammonia or vacuum leads to slightly inferior properties). The as-sintered products have relatively low strengths, and they require heat treatment and/or deformation processing (rolling, extrusion, or forging) for improved properties (Table 2). Applications for sintered aluminum parts include business machines (the largest market), appliances, automotive components, and power tools.

Table 1 Compositions of aluminum P/M alloy powders for pressed-and-sintered parts

Grade	Composition, %				
	Cu	**Mg**	**Si**	**Al**	**Lubricant**
601AB	0.25	1.0	0.6	bal	1.5
201AB	4.4	0.5	0.8	bal	1.5
602AB	. . .	0.6	0.4	bal	1.5
202AB	4.0	. . .	. . .	bal	1.5
MD-22	2.0	1.0	0.3	bal	1.5

MD-24	4.4	0.5	0.9	bal	1.5
MD-69	0.25	1.0	0.6	bal	1.5
MD-76	1.6	2.5	. . .	bal	1.5

Table 2 Mechanical properties of nitrogen-sintered aluminum alloys

Alloy	Tensile strength		Yield strength		Elongation, %
	MPa	**ksi**	**MPa**	**ksi**	
201AB-T6 (95% dense)	336	48.7	322	46.7	2
201AB-T6 (97% dense, rolled)	332	48.2	327	47.4	2
202AB-T6 (92.4% dense)	227	32.9	147	21.3	7.3
202AB-T8 (92.4% dense, cold formed, 19% strain)	280	40.6	250	36.3	3
601AB-T6 (96% dense)	238	34.5	230	33.4	2
601AB-T6 (96% dense, rolled)	252	36.5	241	35.0	2

High-Performance P/M Alloys

Processing

The steps in processing of high-performance aluminum P/M alloys can be combined in various ways, but they are most conveniently described as:

- *Powder production.* Powder can be made by various RS methods including atomization, splat quenching to form particulates, and melt spinning to form ribbon.
- *Powder processing* (optional), which includes mechanical alloying or comminution of melt-spun ribbon into powder for subsequent handling. Mechanical alloying is used for fabricating oxide-dispersion strengthened alloys. Pure metal and alloying ingredients are mechanically alloyed using high-energy ball mills. During this process, a heavy working of powder particles results in the intimate alloying by a process of repeated welding, fracturing, and rewelding. In the case of aluminum alloys, carbon derived form process control agents is incorporated into the processed powder and reacts with aluminum to form very fine carbides. These carbides and the fine oxide particles derived from the breakup of surface films on the initial powder particles create a dispersion that stabilizes the fine-grained microstructure. Therefore, a portion or all of the strengthening may be obtained from the ultrafine grain size stabilized by the oxide and carbide dispersions.
- *Degassing.* Powder is encapsulated in a can and degassed to prevent hydrogen porosity

- *Consolidation.* Powder is vacuum hot pressed or hot isostatically pressed into billets, which are subsequently rolled, extruded, or forged

Classes of High-Performance Alloys

High Room-Temperature Strength SCC/Corrosion-Resistant Alloys. Rapid solidification processing is used to produce Al-Zn-Mg-Cu alloys 7091 and 7090, which are similar in composition to I/M alloy 7175, but contain 0.4 and 1.5% Co, respectively (Table 3). Cobalt forms Co_2Al_9 or $(Co,Fe)_2Al_9$ particles which are homogeneously dispersed. These dispersoids refine the grain size for improved high strength and ductility, and enhance resistance to SCC (Table 4).

Table 3 Nominal compositions of high-strength corrosion-resistant P/M aluminum alloys

Alloy	Composition, wt %							
	Zn	**Mg**	**Cu**	**Co**	**Li**	**O**	**C**	**Al**
7090	7.3-8.7	2.0-3.0	0.6-1.3	1.0-1.9	. . .	0.00-0.50	. . .	bal
7091	6.8-7.1	2.0-3.0	1.1-1.8	0.20-0.60	. . .	0.20-0.50	. . .	bal
Al-9052	. . .	4.0	. . .	. . .	. . .	0.5	1.1	bal

Table 4 Typical room-temperature properties of I/M and P/M high-strength aluminum alloys

Alloy	SCC resistance		Exfoliation rating[(a)]	Ultimate tensile strength		Yield strength[(b)]		Elongation, in 50 mm (2 in.),%	Fracture toughness[(c)]	
	MPa	**ksi**		**MPa**	**ksi**	**MPa**	**ksi**		**MPa**$\sqrt{m}$	**ksi**$\sqrt{in.}$
Ingot metallurgy										
7075-T76	172	25	P, EA	524	76	462	67	12	29	26
7075-T73	290	42	P, EA	503	73	434	63	12	32	29
Powder metallurgy										
7090-T7E71	310	45	N, EA	621	90	579	84	9	26	24
7091-T7E69	310	45	N, EA	593	86	545	79	11	46	42

(a) ASTM exfoliation ratings: N, no appreciable attack; P, pitting--either discrete or blistering; EA, visible lifting of surface; EB, thicker surface attack; EC, more severe surface attack; ED, most severe surface attack.

(b) Longitudinal orientation.

(c) Longitudinal-transverse orientation per ASTM E 399

Mechanically alloyed alloys Al-9052 and Al-905XL (Table 3) also exhibit improved ambient temperature properties and improved corrosion and SCC resistance. Alloy Al-9052 is dispersion strengthened by magnesium oxides, aluminum oxides, and aluminum carbide; solid-solution strengthened by magnesium; and strengthened by its fine grain/subgrain structure. Alloy Al-905XL is strengthened by similar features, although it does display a slight artificial aging response from lithium-containing precipitates. Table 5 lists properties of AL-905XL forgings, and Fig. 1 compares the SCC resistance of RS, MA, and I/M aluminum alloys.

Table 5 Typical mechanical properties of Al-905XL P/M forgings

Material property	Direction	
	Longitudinal	**Transverse**
Ultimate tensile strength		
MPa	517	483
ksi	75	70
Yield strength (0.2% offset)		
MPa	448	414
ksi	65	60
Elongation, %	9	6
Fracture toughness, K_{Ic}		
MPa$\sqrt{m}$	30	30
ksi$\sqrt{in.}$	27	27
Modulus of elasticity		
GPa	80	. . .

10^6 psi	11.6	. . .

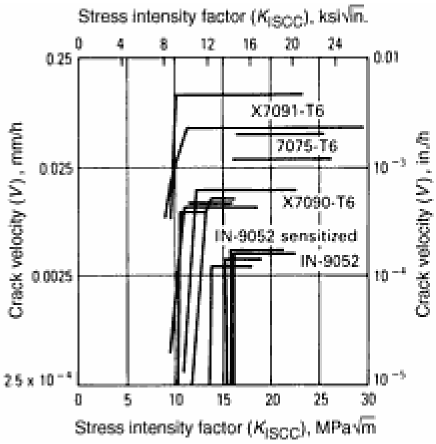


Fig. 1 Crack velocity versus stress intensity factor for P/M alloys Al-9052, 7090, and 7091, as well as conventional alloy 7075. All alloys were in their highest-strength conditions.

Elevated-Temperature Alloys. Conventional high-strength I/M aluminum alloys contain precipitate particles that interact with moving dislocations, thus providing high strength at room temperature. However, when these alloys are exposed to elevated temperatures, the precipitate particles undergo dissolution and/or coarsening, thereby reducing the strength of the base alloy. This behavior precludes the use of these alloys for elevated-temperature applications. The RS-P/M alloys, based on hypereutectic Al-Fe-*X* compositions (Table 6), derive their high strengths from dispersion strengthening; the dispersoids resist dissolution and coarsening when the alloys are exposed to elevated temperatures. These alloys contain ternary and quaternary additions of transition and rare earth metals such as molybdenum, nickel, cerium, vanadium, and silicon. These alloy additions exhibit low solid solubility and low solid-state diffusivity in α aluminum, and consequently, they tend to form thermally stable dispersoid particles. Conventional I/M processing of these compositions produces equilibrium or near-equilibrium microstructures containing coarse Al_3Fe-type primary intermetallic particles in a coarse α-aluminum matrix. Such microstructures exhibit poor ductility and cannot be used for structural applications. In contrast, RS-P/M processing of these chemistries suppresses the formation of Al_3Fe-type primary intermetallic particles. It instead produces particulates exhibiting refined metastable microstructures, such as Al-Al_6Fe-type microeutectic and/or a solute-supersaturated dendritic aluminum. In other words, RS-P/M processing conditions produce refined hypoeutectic-type microstructures from hypereutectic melts. During subsequent thermomechanical processing, the as-solidified hypoeutectic-type microstructures undergo solid-state phase transformations and produce fine (<1 μm) dispersoid particles in an α-aluminum matrix. As shown in Fig. 2, RS-P/M Al-Fe-*X* alloys retain 100% of their strength at temperatures as high as 315 °C (600 °F); conventional I/M alloys retain only about 50% of their strength at this temperature and are generally not used at temperatures exceeding 150 °C (300 °F).

Table 6 Chemical compositions of dispersion-strengthened aluminum-base alloys produced by RS-P/M

Nominal chemical composition, wt %	Manufacturer
Al-8Fe-1.7Ni	Alcoa
Al-8.4Fe-3.7Ce	Alcoa
Al-9Fe-4Ce (AA 8019 alloy)	Alcoa

Al-9Fe-7Ce	Alcoa
Al-10Fe-5Ce	Alcoa
Al-8.5Fe-1.3V-1.7Si (AA 8009 alloy)	AlliedSignal Inc.
Al-11.7Fe-1.2V-2.4Si (FVS 1212 alloy)	AlliedSignal Inc.
Al-8Fe-2.3Mo	Pratt & Whitney
Al-8.7Fe-2.8Mo-1V	Pratt & Whitney

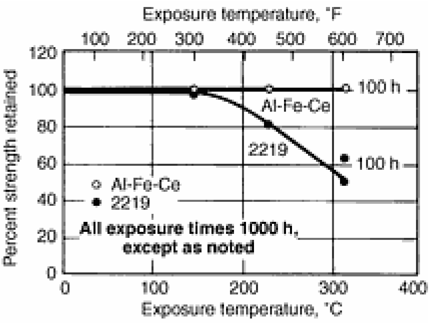


Fig. 2 Percent of room-temperature strength retained after elevated-temperature exposure of Al-Fe-Ce alloys

Low density/high-stiffness alloys include alloying elements that increase the elastic modulus or decrease density. Lithium and beryllium are the only elements that generally increase both properties in aluminum, and RS-P/M, MA, and spray forming have been used to produce Al-Li and Al-Be-Li alloys, Spray forming is a high-deposition-rate metal spraying process for the production of near-net-shape parts at a relatively low cost. In this method, molten metal is rapidly atomized to form a fine spray of droplets that are deposited onto a stationary or moving collector. The resulting preform is typically free from macrosegregation and prior particle boundaries that are occasionally present in I/M products. The spray forming process is useful in extending the maximum solute content of alloying elements and achieving a finer distribution of second-phase particles in an equiaxed grain structure. Such homogeneous, low-segregation, fine-scale alloy microstructures are useful for subsequent rolling, forging, extrusion, and superplastic forming operations. Alloys produced by spray forming can have higher levels of lithium than is possible with I/M alloys (2.5% Li is the practical limit for I/M alloys). Examples of spray-formed Al-Li alloys include Al-3.0Li-1.0Cu-0.7Mg-0.3Zr and Al-4Li-0.2Zr, both of which have higher levels of lithium and zirconium than does the commonly used I/M Al-Li alloy 8090 (Al-2.5Li-1.0Cu-0.7Mg-0.12Zr). The P/M Al-Li alloys exhibit a 4.4% increase in specific modulus over 8090.

Neither the Al-Li or Al-Be-Li P/M alloys have achieved commercial success, largely because of the success of I/M Al-Li alloys and the development of metal-matrix composites, such as Al-SiC and Al-TiB_2 systems. Examples of aluminum-matrix composites produced by P/M processing are described in the Section "Special-Purpose Materials" in this Handbook.

Corrosion Resistance of Aluminum and Aluminum Alloys

Introduction

ALUMINUM and most aluminum alloys have good corrosion resistance in natural atmospheres, fresh waters, seawater, many soils, many chemicals and their solutions, and most foods. This resistance to corrosion is the result of the presence of a very thin, compact, and adherent film of aluminum oxide on the metal surface. Whenever a fresh surface is created by cutting or abrasion and is exposed to either air or water, a new film forms rapidly, growing to a stable thickness. The film formed in air at ambient temperatures is ∼5 nm (50 Å) thick. The thickness increases with increasing temperature and in the presence of water. The oxide film is soluble in alkaline solutions and in strong acids, with some exceptions, but is stable over a pH range of ∼4.0 to 9.0.

There are different types of corrosion and various interactions with induced or imposed stresses so that the effects can range from unimportant to highly damaging. For some types of applications, a distinction should be made between appearance and durability. The surface can become unattractive because of roughening by shallow pitting and can darken with dirt retention, but these conditions may have no effect on durability or function. On the other hand, stress-corrosion cracking (SCC) or highly localized, severe corrosion due to heavy-metal ions in solutions, stray electrical currents, or galvanic couples with more-anodic metals can be quite damaging. Good design and application practices must be observed to avoid these conditions. This includes selection of alloys appropriate for the conditions of the application.

Effects of Alloy Composition

Among the principal alloying elements (magnesium, silicon, copper, manganese, and zinc), the element that has the greatest effect on general corrosion resistance is copper. Copper reduces resistance because it replates from solution as minute metallic particles forming highly active corrosion couples. The effects are apparent at copper contents exceeding a few tenths of one percent. In the heat treatable 2*xxx* or 2*xx.x* alloys with several percent copper, the state of solution or precipitation affects the type of corrosion attack as well as susceptibility to SCC. These effects are recognized in the alloy/temper ratings for general corrosion and SCC that appear in Table 1 for wrought alloys and Table 2 for casting alloys.

Table 1 Relative ratings of resistance to general corrosion and to SCC of wrought aluminum alloys

Alloy		Resistance to corrosion	
No.	**Temper**	**General(a)**	**SCC(b)**
1060	All	A	A
1100	All	A	A
1350	All	A	A
2011	T3, T4, T451	D(c)	D
	T8	D	B
2014	O	. . .	. . .

	T3, T4, T451	D(c)	C
	T6, T651, T6510, T6511	D	C
2017	T4, T451	D(c)	C
2018	T61	. . .	. . .
2024	O	. . .	. . .
	T4, T3, T351, T3510, T3511, T361	D(c)	C
	T6, T861, T81, T851, T8510, T8511	D	B
	T72	. . .	. . .
2025	T6	D	C
2036	T4	C	. . .
2117	T4	C	A
2218	T61, T72	D	C
2219	O	. . .	. . .
	T31, T351, T3510, T3511, T37	D(c)	C
	T81, T851, T8510, T8511, T87	D	B
2618	T61	D	C
3003	All	A	A
3004	All	A	A
3105	All	A	A
4032	T6	C	B
5005	All	A	A

5050	All	A	A
5052	All	A	A
5056	O, H11, H12, H32, H14, H34	A[(d)]	B[(d)]
	H18, H38	A[(d)]	C[(d)]
	H192, H392	B[(d)]	D[(d)]
5083	All	A[(d)]	B[(d)]
5086	O, H32, H116	A[(d)]	A[(d)]
	H34, H36, H38, H111	A[(d)]	A[(d)]
5154	All	A[(d)]	A[(d)]
5252	All	A	A
5254	All	A[(d)]	A[(d)]
5454	All	A	A
5456	All	A[(d)]	B[(d)]
5457	O	A	A
5652	All	A	A
5657	All	A	A
6053	O	. . .	. . .
	T6, T61	A	A
6061	O	B	A
	T4, T451, T4510, T4511	B	B
	T6, T651, T652, T6510, T6511	B	A

6063	All	A	A
6066	O	C	A
	T4, T4510, T4511, T6, T6510, T6511	C	B
6070	T4, T4511, T6	B	B
6101	T6, T63, T61, T64	A	A
6151	T6, T652	. . .	. . .
6201	T81	A	A
6262	T6, T651, T6510, T6511, T9	B	A
6463	All	A	A
7001	O	C(c)	C
7075	T6, T651, T652, T6510, T6511	C(c)	C
	T73, T7351	C	B
7178	T6, T651, T6510, T6511	C(c)	B

(a) Ratings are relative and in decreasing order of merit, based on exposure to sodium chloride solution by intermittent spraying or immersion. Alloys with A and B ratings can be used in industrial and seacoast atmospheres without protection. Alloys with C, D, and E ratings generally should be protected, at least on faying surfaces.

(b) Stress-corrosion cracking ratings are based on service experience and on laboratory tests of specimens exposed to alternate immersion in 3.5% NaCl solution. A, no known instance of failure in service or in laboratory tests; B, no known instance of failure in service; limited failure in laboratory tests of short transverse specimens; C, service failures when sustained tension stress acts in short-transverse direction relative to grain structure; limited failures in laboratory tests of long transverse specimens; D, limited service failures when sustained stress acts in longitudinal or long-transverse direction relative to grain structure.

(c) In relatively thick sections, the rating would be E.

(d) This rating may be different for material held at elevated temperatures for long periods.

Table 2 Relative ratings of resistance to general corrosion and to SCC of cast aluminum alloys

Alloy	Resistance to corrosion

No.	**Temper**	**General**[(a)]	**SCC**[(b)]
Sand castings			
208.0	F	B	B
224.0	T7	C	B
240.0	F	D	C
242.0	All	D	C
A242.0	T75	D	C
249.0	T7	C	B
295.0	All	C	C
319.0	F, T5	C	B
	T6	C	C
355.0	All	C	A
C355.0	T6	C	A
356.0	T6, T7, T71, T51	B	A
A356.0	T6	B	A
443.0	F	B	A
512.0	F	A	A
513.0	F	A	A
514.0	F	A	A
520.0	T4	A	C
535.0	F	A	A

B535.0	F	A	A
705.0	T5	B	B
707.0	T5	B	C
710.0	T5	B	B
712.0	T5	B	C
713.0	T5	B	B
771.0	T6	C	C
850.0	T5	C	B
851.0	T5	C	B
852.0	T5	C	B
Permanent mold castings			
242.0	T571, T61	D	C
308.0	F	C	B
319.0	F	C	B
	T6	C	C
332.0	T5	C	B
336.0	T551, T65	C	B
354.0	T61, T62	C	A
355.0	All	C	A
C355.0	T61	C	A
356.0	All	B	A

A356.0	T61	B	A
F356.0	All	B	A
A357.0	T61	B	A
358.0	T6	B	A
359.0	All	B	A
B443.0	F	B	A
A444.0	T4	B	A
513.0	F	A	A
705.0	T5	B	B
707.0	T5	B	C
711.0	T5	B	A
713.0	T5	B	B
850.0	T5	C	B
851.0	T5	C	B
852.0	T5	C	B
Die castings			
360.0	F	C	A
A360.0	F	C	A
364.0	F	C	A
380.0	F	E	A
A380.0	F	E	A

383.0	F	E	A
384.0	F	E	A
390.0	F	E	A
392.0	F	E	A
413.0	F	C	A
A413.0	F	C	A
C443.0	F	B	A
C443.0	F	B	A
518.0	F	A	A
Rotor metal(c)			
100.1	. . .	A	A
150.1	. . .	A	A
170.1	. . .	A	A

(a) Relative ratings of general corrosion resistance are in decreasing order of merit, based on exposures to NaCl solution by intermittent spray or immersion.

(b) Relative ratings of resistance to SCC are based on service experience and on laboratory tests of specimens exposed to alternate immersion in 3.5% NaCl solution. A, no known instance of failure in service when properly manufactured; B, failure not anticipated in service from residual stresses or from design and assembly stresses below about 45% of the minimum guaranteed yield strength given in applicable specifications; C, failures have occurred in service with either this specific alloy/temper combination or with alloy/temper combinations of this type; designers should be aware of the potential SCC problem that exists when these alloys and tempers are used under adverse conditions.

(c) For electric motor rotors

Among the common impurity elements, iron is probably the most important, degrading general corrosion resistance by increasing the volume fraction of cathodic and surface-film-weakening intermetallic-phase microconstituents.

The 7*xxx* Al-Zn-Mg alloys without copper have high general corrosion resistance. The alloys of this group that contain more than 1% Cu are less resistant to general corrosion. Appropriate tempers should be used to avoid SCC.

The 3*xxx* alloys are generally among those having the highest general corrosion resistance, as are those of the 5*xxx* group, which outperform any of the others in marine exposures. The 6*xxx* alloys also have high resistance.

Corrosion in Atmospheres

Alloys other than those with the higher copper contents have excellent resistance to atmospheric corrosion (often called weathering) and in many outdoor applications require no protection or maintenance. Products widely used under such conditions include electrical conductors, outdoor lighting poles, bridge railings, and ladders. These often retain a bright metallic appearance for many years but may darken with mild surface roughening caused by shallow pitting and with accumulation of dirt.

An important characteristic of weathering, as well as corrosion of aluminum under many other environmental conditions, is that the rate of corrosion decreases with time. Figure 1 shows typical curves of the average changes that occurred in exposures of two generic types, seacoast and industrial, over a 30 year period with sheet specimens of 1100, 3003, and 3004 alloys, all in H14 temper. The curve shapes are similar, whether the amount of corrosion is measured by weight loss, depth of pitting, or loss in strength. Leveling-off usually occurs in 6 months to 2 years, after which the rate becomes approximately linear at a low rate. In rural atmospheres the weight-loss rate may be less than 0.025 μm/year (0.001 mil/year). In industrial locations, rates vary from ~0.75 to 2.75 μm/year (0.03 to 0.11 mil/year) with a few particularly aggressive sites at which rates up to 12.5 μm/year (0.5 mil/year), based on maximum pit depth, were observed. Table 3 compares atmospheric corrosion rates for wrought aluminum alloy 1100-H14 with that of commercially pure copper, lead, and zinc.

Table 3 Atmospheric corrosion rates for aluminum and other nonferrous metals at several exposure sites

Location	Type of atmosphere	Depth of metal removed per side[(a)], in μm/yr, during exposure of indicated length for specimens of							
		Aluminum[(b)]		**Copper**[(c)]		**Lead**[(d)]		**Zinc**[(e)]	
		10 yr	**20 yr**	**10 yr**	**20 yr**	**10 yr**	**20 yr**	**10 yr**	**20 yr**
Phoenix, AZ	Desert	0.000	0.076	0.13	0.13	0.23	0.10	0.25	0.18
State College, PA	Rural	0.025	0.076	0.58	0.43	0.48	0.30	1.07	1.09
Key West, FL	Seacoast	0.10	. . .	0.51	0.56	0.56	. . .	0.53	0.66
Sandy Hook, NJ	Seacoast	0.20	0.28	0.66	. . .	. . .	. . .	1.40	. . .
La Jolla, CA	Seacoast	0.71	0.63	1.32	1.27	0.41	0.53	1.73	1.73
New York, NY	Industrial	0.78	0.74	1.19	1.37	0.43	0.38	4.8	5.6
Altoona, PA	Industrial	0.63	. . .	1.17	1.40	0.69	. . .	4.8	6.9

(a) Calculated from weight loss, assuming uniform attack, for 0.89 mm (0.035 in.) thick panels.

(b) Aluminum 1100-H14.

(c) Tough pitch copper (99.9% Cu).

(d) Commercial lead (99.92% Pb).

(e) Prime western zinc (98.9% Zn)

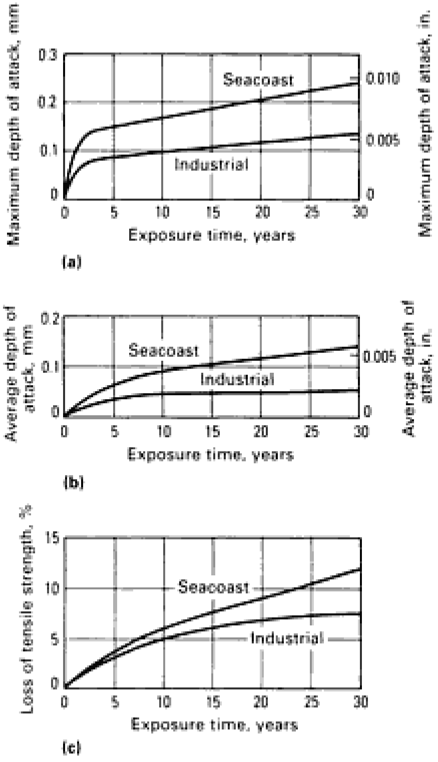


Fig. 1 Depth of corrosion and loss of tensile strength for alloys 1100, 3003, and 3004 (shown in graphs a, b, and c, respectively). Data are given for the average performance of the three alloys, all in the H14 temper. Seacoast exposure was at a severe location (Pt. Judith, RI); industrial exposure was at New Kensington, PA. Tensile strengths were computed using original cross-sectional areas, and loss in strength is expressed as a percentage of original tensile strength.

Castings of 4*xx.x* and low-copper 3*xx.x* alloys have been used for many years in such applications as bridge guard-rail supports and lighting-pole bases with little adverse effect from corrosion. The 5*xx.x* casting alloys with 4 to 8% Mg are particularly suitable for cast parts that are used in marine and seawater exposure sites. Copper-containing alloys such as 295.0, 333.0, 380.0, and even 355.0 require surface protection for satisfactory use in corrosive marine or industrial atmospheres. Stress-corrosion cracking has been encountered occasionally with some of the 7*xx.x* alloys and alloy 520.0-T4 in atmospheric exposures of stressed parts. Applications for these alloys must be carefully engineered to avoid such problems.

Corrosion in Waters

Corrosion resistance of aluminum in high-purity water, distilled or deionized, and in steam condensate is so high that these fluids are regularly contained and handled in aluminum equipment. Resistance is also high in most natural fresh waters. Soft waters have the least pitting tendency. Components of natural waters that increase pitting are copper ions, bicarbonate, chloride, sulfate, and oxygen. Thus, harder waters with more bicarbonate have a higher pitting tendency.

Service experience with aluminum alloys in marine and coastal applications, including structures, buoys, pipelines, lifeboats, motor launches, cabin cruisers, patrol boats, barges and larger vessels, has demonstrated their good resistance and long life under conditions of partial, intermittent, and total immersion. Wrought alloys of the 3*xxx*, 5*xxx*, and 6*xxx* groups are used. Those alloys of the 5*xxx* aluminum-magnesium group are most resistant and most widely used because of favorable strength and good weldability. The rate of corrosion based on weight loss does not exceed ~5 μm/year (0.2 mil/year), which is <5% of the rate for unprotected low-carbon steel in seawater. Corrosion is mainly pitting, decelerating with time from rates of 2.5 to 5 μm/year (0.1 to 0.2 mil/year) in the first year to average rates over a 10 year period of 0.75 to 1.5 μm/year (0.03 to 0.06 mil/year). The curve of maximum depth of pitting versus time follows an approximate cube-root law, from which it follows that doubling material thickness increases time to perforation by a factor of 8.

Casting alloys of the 5*xx.x* group with up to 8% Mg have high resistance to seawater corrosion and are used for fittings. Al-Si and Al-Si-Mg alloys are less resistant although 443.0 and 356.0T6 are sometimes used. Resistance of 2*xxx*, 2*xx.x*, 7*xxx,* and 7*xx.x* alloys is distinctly inferior, and their use without cladding or metallizing is not recommended.

Corrosion in Soils

Soils differ widely in mineral content, texture, permeability, moisture, pH, and electrical conductivity as well as aeration, organic matter, and microorganisms. With this variability, corrosion performance of unprotected buried aluminum, like that of other metals, varies considerably. However, in many cases where carbon steel requires protective coatings, unprotected aluminum alloys have performed well. In most cases protection is recommended for buried applications. Use of 2*xxx* or 7*xxx* alloys or their cast counterparts is generally not recommended. Stray-current effects and contact with more-cathodic metals should be avoided. Successful applications include pipelines employing alloys 3003, 6061, and 6063 and culverts made of alclad 3004.

Exposure to Foods

Aluminum alloys of the 3*xxx* and 5*xxx* groups are resistant to most foods and beverages. Aluminum products constitute a substantial share of the domestic cooking-utensil market and are used extensively for commercial handling and processing of foods. Large quantities of foil, foil laminated to plastics or paper, and cans are used for packaging and marketing of foods and beverages. Beverage-can bodies are generally produced from alloy 3004, food-can bodies from 5352 or 5050, and can ends from 5182. These cans generally have internal and external organic coatings, not for corrosion protection, but for decoration and prevention of effects on product taste.

Exposure to Chemicals

Aluminum alloys are used in storing, processing, handling, and packaging of a variety of chemical products. They are compatible with most dry inorganic salts. Within the passive pH range, about 4 to 9, they resist corrosion in solutions of most inorganic chemicals but are subject to pitting in aerated solutions, particularly of halides. Aluminum alloys are not suitable for containing or handling mineral acids with the exceptions of nitric acid in concentrations over 82 wt% and sulfuric acid in concentrations from 98 to 100 wt%.

Aluminum alloys resist most alcohols; however, some may cause corrosion when extremely dry and at elevated temperatures. Similar characteristics are associated with phenol. Aldehydes have little or no corrosive effects. Care must be taken in using aluminum with halogenated organic compounds because under some conditions when moisture is present, they may hydrolyze and react violently.

Resistance of aluminum and aluminum alloys to many foods and chemicals, representing practically all classifications, has been established in laboratory tests and, in many cases, by service experience. Data are readily available from handbooks, proprietary literature, and trade association publications. (See, for example, *Guidelines for the Use of Aluminum with Food and Chemicals* published by the Aluminum Association Inc.)

Exposure to Nonmetallic Building Materials

Aluminum alloys are not corroded seriously by long-time embedment in portland cement concrete, standard or lime brick mortar, hardwall plaster, or stucco. Superficial etching of the aluminum occurs while these products are setting, but after curing further attack is minimal. Special consideration should be given to protection where crevices between the concrete and the metal can entrap environmental contaminants. For example, highway railings and streetlight standards or stanchions usually are coated with a sealing compound where they are fastened to concrete, to prevent entry of salt-laden road splash into crevices.

Absorbent materials, such as paper, wood refuse, and wallboard in contact with aluminum under conditions where it may become wet, will cause corrosion. Composite-bonded insulated aluminum panels employ a moisture barrier on the inside to prevent condensation and wetting of the insulation. Some insulating materials, such as magnesia, are alkaline and quite aggressive to aluminum. Magnesium oxychloride, a flooring compound sometimes used in subway and railway passenger cars and ship decks, is very corrosive and should not be used with aluminum. Although wood usually is not corrosive, it can become corrosive if moisture content exceeds 18 to 20%. Wood preservatives containing copper are detrimental, and those containing mercury should not be used where aluminum is involved.

Forms of Corrosion

Form or type of corrosion can be categorized by the morphology, which may or may not be related to the microstructure of the metal, or by the conditions causing the corrosion. Uniform attack or dissolution, which may occur if the surface oxide film is soluble in the corroding medium, is infrequent in service. Most corrosion in service is localized in one way or another. When the oxide film is insoluble in the corroding medium, corrosion is localized at weak spots in the film, which can result from microstructural features such as the presence of microconstituents. Local cells are formed by such nonuniformities in the metal as well as environmental nonuniformities, such as those created by differential aeration cells or by heavy metals plated out on the surface. Localized corrosion in a microscopic sense results from galvanic coupling and stray-current effects.

Pitting is the most common form of localized corrosion and frequently is difficult to associate with specific metallographic features. Pit shape can vary from shallow depressions to cylindrical or roughly hemispherical cavities. These shapes distinguish pitting from intergranular or exfoliation corrosion. Superpurity aluminum has the highest resistance to pitting, and, among the 1*xxx* and 1*xx.x* aluminums, resistance improves with purity. Among commercial alloys, those of the 5*xxx* group have the lowest pitting probability and penetration rates, followed by alloys of the 3*xxx* group.

Intergranular corrosion is a selective attack of grain boundaries. The mechanism is electrochemical, resulting from local cell action in the boundaries. Microconstituents precipitated in grain boundaries have a corrosion potential differing from that of adjacent solid solution and transition precipitate structure and form cells with it. In alloys of the 5*xxx* and 7*xxx* groups, the precipitates (Al_8Mg_5, $MgZn_2$, and $Al_2Mg_3Zn_3$) are anodic to the matrix. In 2*xxx* alloys, the precipitates (Al_2Cu and Al_2CuMg) are cathodic. Intergranular corrosion can occur with either type. Susceptibility depends on the extent of intergranular precipitation, which is controlled by fabricating or heat treating parameters.

In 2*xxx* alloys, grain-boundary precipitation is caused by an inadequate cooling rate during the quenching operation of heat treatment. Thick-section products cannot be cooled sufficiently rapidly to completely avoid susceptibility to intergranular corrosion in T3- and T4-type tempers. Resistance to this type of attack is much higher in T6- and T8-type tempers. Alloys of the 6*xxx* group with a balanced magnesium/silicon ratio (Mg_2Si proportions) show little tendency toward intergranular corrosion; susceptibility is higher in those with excess silicon over the Mg_2Si ratio. Alloys of the 7*xxx* group may corrode intergranularly; overaging to T7-type tempers provides high resistance.

Because intergranular corrosion is involved in SCC of aluminum alloys (see discussion below), it is often presumed to be more deleterious than pitting or general (uniform) corrosion. However, in alloys that are not susceptible to SCC--for example, the 6*xxx* series alloys--intergranular corrosion is usually no more severe than pitting corrosion, tends to decrease with time, and, for equal depth of corrosion, the effect on strength is no greater than that of pitting corrosion, although fatigue cracks can be more likely to initiate at areas of intergranular corrosion than at random pits.

Exfoliation corrosion is selective attack that proceeds along multiple subsurface paths roughly parallel to the surface. It can be intergranular but also is associated with striated insoluble microconstituents and dispersoid bands aligned parallel to the product surface. It is most common in thin-section products with highly worked, flattened, and elongated metallurgical structures. Leafing or delamination accompanied by swelling caused by expansion of corrosion products is characteristic and is apparent in metallographic section (see Fig. 2). Exfoliation frequently proceeds from sheared edges and may be initiated at pit surfaces. It is not accelerated by applied stress but is intensified by slightly acidic solutions and by galvanic coupling.

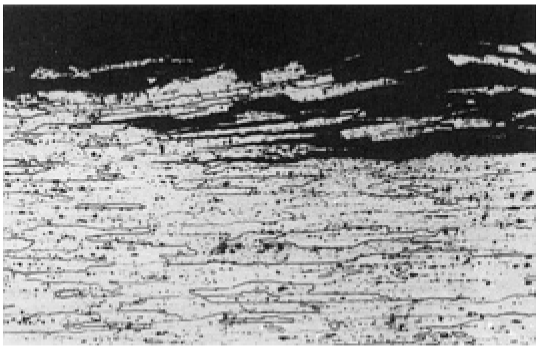


Fig. 2 Exfoliation corrosion in an alloy 7178-T651 plate exposed to a seacoast environment. Cross section of the plate shows how exfoliation develops by corrosion along boundaries of thin, elongated grains.

In 2*xxx* and copper-containing 7*xxx* alloys, exfoliation is considerably affected by section thickness and corresponding microstructure and by temper. The 2*xxx* alloys are susceptible only in T3- and T4-type tempers and are resistant in T6- or T8-type tempers. In the copper-containing 7*xxx* group alloys, resistance is greatly improved by overaging beyond peak strength (T6-type tempers), so that these materials are resistant in T7-type tempers. In extrusions of these heat-treated alloys, the recrystallized peripheral zone near surfaces is often highly resistant to exfoliation while the underlying unrecrystallized portion may be vulnerable to this type of attack.

The 1*xxx* aluminums and 3*xxx* alloys are highly resistant to exfoliation in all tempers. Exfoliation has been encountered in highly cold worked, high-magnesium 5*xxx* alloys such as 5456-H321 boat hull plate. Improved tempers (H116 and H117) with high resistance have been established.

Galvanic Corrosion. Most forms of corrosion discussed previously are electrochemical in nature and involve cells formed by microstructural or environmental features. A number of other conditions establish potential differences that intensify and localize corrosion. The accelerated corrosion resulting from electrical contact with a more-noble metal or with a nonmetallic conductor such as graphite is termed "galvanic corrosion." The most common examples occur when aluminum alloys are joined to steel or copper and are exposed to wet saline environments. In such situations the aluminum is more rapidly corroded than it would be in the absence of the dissimilar metal.

For each environment, metals can be arranged in a galvanic series from most to least active. Table 4 lists potentials based on measurements in sodium chloride solution. The rate of corrosive attack when two metals are coupled depends on several factors: (a) the potential difference, (b) the electrical resistance between the metals, (c) the conductivity of the electrolyte, (d) the cathode/anode area ratio, and (e) the polarization characteristics of the metals. Although the corrosion potential can be used to predict which metal will be attacked galvanically, the extent of attack cannot be predicted because of polarization. For example, the potential difference between aluminum and stainless steel exceeds that between aluminum and copper; however, the galvanic effect of stainless steel on aluminum, because of polarization, is much less than that of copper, which shows little polarization.

Table 4 Electrode potentials of representative aluminum alloys and other metals

Aluminum ally[(a)] or other metal	Potential[(b)], V
Chromium	+0.18 to -0.40
Nickel	-0.07
Silver	-0.08

Stainless steel (300 series)	-0.09
Copper	-0.20
Tin	-0.49
Lead	-0.55
Mild carbon steel	-0.58
2219-T3,-T4	-0.64(c)
2024-T3,-T4	-0.69(c)
295.0-T4 (S or PM)	-0.70
2014-T6, 355.0-T4(S or PM)	-0.78
355.0-T6(S or PM)	-0.79
2219-T6, 6061-T4	-0.80
2024-T6	-0.81
2219-T8, 2024-T8, 356.0-T6 (S or PM), 443.0-F (PM), cadmium	-0.82
1100, 3003, 6061-T6, 6063-T6, 7075-T6(c), 443.0-F (S)	-0.83
1060, 1350, 3004, 7050-T73(c), 7075-T73(c)	-0.84
5052, 5086	-0.85
5454	-0.86
5456, 5083	-0.87
7072	-0.96
Zinc	-1.10

Magnesium	-1.73

(a) The potential of an aluminum alloy is the same in all tempers wherever the temper is not designated. S is sand cast; PM is permanent mold cast.

(b) Measured in an aqueous solution of 53 g of sodium chloride and 3 g of H_2O_2 per liter at 25 °C; 0.1*N* calomel reference electrode.

(c) Potential varies ±0.01 to 0.02 V with quenching rate.

In natural environments, including saline solutions, zinc is anodic to aluminum and corrodes preferentially, giving protection to the aluminum. Magnesium is also protective, although in severe marine environments, it can cause corrosion of aluminum because of an alkaline reaction. Cadmium is neutral to aluminum and can be used safely in contact with it. Copper and copper alloys, brass, bronze, and monel are the most harmful, followed closely by carbon steel in saline environments. Nickel is less aggressive than copper, approaching stainless steel in effect, as does chromium electroplate. Lead can be used with aluminum, except in marine environments.

Stray-Current Corrosion. Whenever an electric current is conducted from aluminum to an environment such as water, soil, or concrete, the aluminum is corroded in the area of anodic reaction in proportion to the current. At low current densities, the corrosion may be in the form of pitting, while at higher current densities, considerable metal destruction can occur at rates that do not diminish with time.

In soils, stray-current corrosion can be caused by close proximity to other buried metal systems, which are protected by an impressed-current cathodic-protection system. The ground current can leak onto a buried aluminum structure at one point, then off at another where the corrosion occurs, taking a lower-resistance path between the driven buried anode and the nearby structure being protected. Common bonding of all buried metal systems in close proximity is the usual way to avoid such attack.

Deposition corrosion is a special form of galvanic corrosion that causes pitting. It occurs when particles of a more-cathodic metal plate out of solution on the aluminum surface, setting up local galvanic cells. The ions aggressive to aluminum are copper, lead, mercury, nickel and tin, often referred to as heavy metals. Their effects are greater in acidic solutions and are much less severe in alkaline solutions in which their solubility is low.

Copper ions most commonly cause this type of corrosion in applications of aluminum. For example, rain runoff from copper roof flashing can cause corrosion of aluminum gutters with no electrical contact between the two metals. Very small amounts of copper in solution (as low as 0.05 ppm) can be detrimental. The inferior general corrosion resistance of alloys containing copper is attributed to deposition corrosion by copper replated from the dissolved corrosion products.

Mercury is the ion most aggressive to aluminum, and even traces can cause serious problems. Liquid mercury does not wet aluminum, but if the natural oxide film on the aluminum surface is broken, aluminum dissolves in the mercury, forming amalgam, and the corrosion reaction becomes catastrophic. In corrosive solutions, any concentration of mercury greater than a few parts per billion should be cause for concern.

Crevice Corrosion. If an electrolyte is present in a crevice formed between two facing aluminum surfaces or between an aluminum surface and a nonmetallic material such as a gasket, localized corrosion in the form of pits or etch patches can occur. This is the result of formation of a concentration cell or differential aeration cell. Staining that occurs on inter-wrap surfaces of coiled sheet or foil or in packages of flat sheet or circles is a result of the same mechanism and can be preliminary to more severe corrosion that will make separation difficult. Such damage can be prevented by ensuring that the product is initially dry and by avoiding ingress of moisture by protecting it against condensation, rain, and other sources of contamination.

Filiform corrosion, sometimes termed "worm-track" corrosion, occurs on aluminum when it is coated with an organic coating and exposed to warm, humid atmospheres. The corrosion appears as threadlike filaments that initiate at defects in the organic coating, are activated by chlorides, and grow along the metal/coating interface at rates to 1 mm/day (0.04

in./day). The moving end of the filament is called the head, and the remainder of the track is called the tail (Fig. 3a). The occurrence of filiform corrosion on painted surfaces in aircraft (Fig. 3b) exposed to marine and other high-humidity environments has been controlled by use of chemical conversion coatings, anodizing, or application of chromate-inhibited primers prior to final coating.

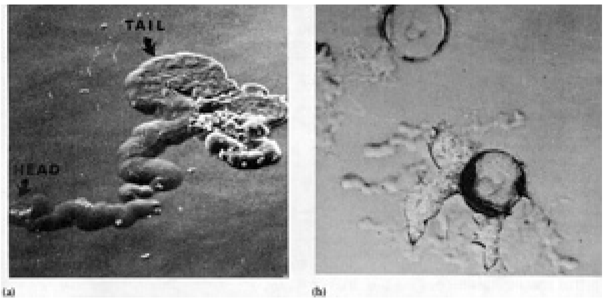


Fig. 3 Examples of filiform corrosion of aluminum. (a) Aluminum foil coated with polyvinyl chloride showing the advancing head and cracked tail section of a filiform cell. SEM. 80×. (b) Filiform corrosion of a painted aluminum aircraft skin

Stress-Corrosion Cracking. Time-dependent cracking under the combined influence of sustained tensile stress and a corrosive environment is labeled SCC. In aluminum products, SCC, which is characteristically intergranular in nature, has been experienced only in higher-strength alloys and tempers of the 2*xxx*, 7*xxx*, and 5*xxx* types (with more than 3% Mg) and of the 6*xxx* type (with excess silicon). The relative resistances of aluminum products made of such alloys in various tempers, and with respect to the direction of tensile stress, is indicated by the ratings listed in Table 5. No SCC problems have been encountered in service with 1*xxx* aluminum or with 3*xxx*, 6*xxx* (Mg_2Si ratio) or 5*xxx* (containing 3% Mg or less) alloys. 6061-T6, which is included in Table 5, is a balanced-ratio alloy.

Table 5 Relative stress-corrosion-cracking ratings for wrought products of high-strength aluminum alloys

Alloy and temper(a)	Test direction(b)	Rolled plate	Rod and bar(c)	Extruded shapes	Forgings
2011-T3, -T4	L	(d)	B	(d)	(d)
	LT	(d)	D	(d)	(d)
	ST	(d)	D	(d)	(d)
2011-T8	L	(d)	A	(d)	(d)
	LT	(d)	A	(d)	(d)
	ST	(d)	A	(d)	(d)
2014-T6	L	A	A	A	B
	LT	B(e)	D	B(e)	B(e)

	ST	D	D	D	D
2024-T3, -T4	L	A	A	A	(d)
	LT	B(e)	D	B(e)	(d)
	ST	D	D	D	(d)
2024-T6	L	(d)	A(d)	A	
	LT	(d)	B	(d)	A(e)
	ST	(d)	B	(d)	D
2024-T8	L	A	A	A	A
	LT	A	A	A	A
	ST	B	A	B	C
2124-T851	L	A	(d)	(d)	(d)
	LT	A	(d)	(d)	(d)
	ST	B	(d)	(d)	(d)
2219-T3, -T37	L	A	(d)	A	(d)
	LT	B	(d)	B	(d)
	ST	D	(d)	D	(d)
2219-T6, -T8	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A
6061-T6	L	A	A	A	A
	LT	A	A	A	A

	ST	A	A	A	A
7005-T53, -T63	L	(d)	(d)	A	A
	LT	(d)	(d)	A(e)	A(e)
	ST	(d)	(d)	D	D
7039-T63, -T64	L	A	(d)	A	(d)
	LT	A(e)	(d)	A(e)	(d)
	ST	D	(d)	D	(d)
7049-T73	L	A	(d)	A	A
	LT	A	(d)	A	A
	ST	A	(d)	B	A
7149-T73	L	(d)	(d)	A	A
	LT	(d)	(d)	A	A
	ST	(d)	(d)	B	A
7050-T74	L	A	(d)	A	A
	LT	A	(d)	A	A
	ST	B	(d)	B	B
7050-T74	L	A	(d)	A	A,
	LT	A	(d)	A	A
	ST	B	(d)	B	B
7050-T76	L	A	A	A	(d)
	LT	A	B	A	(d)

	ST	C	B	C	(d)
7075-T6	L	A	A	A	A
	LT	B(e)	D	B(e)	B(e)
	ST	D	D	D	D
7075-T73	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A
7075-T736	L	(d)	(d)	(d)	A
	LT	(d)	(d)	(d)	A
	ST	(d)	(d)	(d)	B
7075-T76	L	A	(d)	A	(d)
	LT	A	(d)	A	(d)
	ST	C	(d)	C	(d)
7175-T736	L	(d)	(d)	(d)	A
	LT	(d)	(d)	(d)	A
	ST	(d)	(d)	(d)	B
7475-T6	L	A	(d)	(d)	(d)
	LT	B(e)	(d)	(d)	(d)
	ST	D	(d)	(d)	(d)
7475-T73	L	A	(d)	(d)	(d)
	LT	A	(d)	(d)	(d)

	ST	A	(d)	(d)	(d)
7475-T76	L	A	(d)	(d)	(d)
	LT	A	(d)	(d)	(d)
	ST	C	(d)	(d)	(d)
7178-T6	L	A	(d)	A	(d)
	LT	B(e)	(d)	B(e)	(d)
	ST	D	(d)	D	(d)
7178-T76	L	A	(d)	A(e)	(d)
	LT	A	(d)	A	(d)
	ST	C	(d)	C	(d)
7079-T6	L	A	(d)	A	A
	LT	B(e)	(d)	B(e)	B(e)
	ST	D	(d)	D	D

Resistance ratings are as follows: A, very high, no record of service problems, stress-corrosion cracking not anticipated in general applications, B, high, no record of service problems, stress-corrosion cracking not anticipated at stresses of the magnitude caused by solution heat treatment. Precautions must be taken to avoid high sustained tensile stresses (exceeding 50% of the minimum specified yield strength) produced by any combination of sources, including heat treatment, straightening, forming, fit up, and sustained service loading. C, intermediate. Stress-corrosion cracking not anticipated if total sustained tensile stress is maintained below 25% of minimum specified yield strength. This rating is designated for the short-transverse direction in products used primarily for high resistance to exfoliation corrosion in relatively thin structures, where appreciable stresses in the short-transverse direction are unlikely, D, low. Failure from stress-corrosion cracking is anticipated in any application involving sustained tensile stress in the designated test direction. This rating is currently designated only for the short-transverse direction in certain products.

(a) Ratings apply to standard mill products in the types of tempers indicated and also in T*x*5*x* and T*x*5*xxx* (stress-relieved) tempers, and may be invalidated in some instances by use of nonstandard thermal treatments, or mechanical deformation at room temperature by the user.

(b) Test direction refers to orientation of direction in which stress is applied relative to the directional grain structure typical of wrought alloys, which for extrusions and forgings may not be predictable on the basis of the cross-sectional shape orientation of direction in which stress is applied relative to the directional grain structure typical of wrought alloys, which for extrusions and forgings may not be predictable on the basis of the cross-sectional shape of the product: L, longitudinal; LT, long transverse; ST, short transverse.

(c) Sections with width-to-thickness ratios equal to or less than two, for which there is no distinction between LT and ST properties.

(d) Rating not established because product not offered commercially.

(e) Rating is one class lower for thicker sections: extrusions, 25mm (1 in.) and thicker; plate and forgings, 40mm (1.5 in.) and thicker

In general, high-tensile stress is a prerequisite to cracking when the stress direction is parallel to either the longitudinal or the long-transverse direction. When the tensile stress is in the short-transverse direction (perpendicular to the surfaces of plate or across the flash plane of die forgings), SCC can occur in susceptible alloy/temper combinations at relatively low stresses. Cracking is accelerated by aggressive, chloride-containing environments, but can occur in humid air.

Because of the orientation-dependence of SCC, it is important to minimize stresses in the most susceptible direction. In addition to the stresses imposed by service loading, the residual stresses from quenching or forming, and any resulting from interference fits or assembly misfits, must be taken into account. Minimizing these stresses in the short-transverse direction greatly reduces the probability of SCC failure of susceptible alloy/temper combinations. Use of resistant tempers is recommended.

For thin-section products used under conditions that induce little or no stress in the short-transverse direction, resistance of 2*xxx* alloys in T3- or T4-type tempers or of 7*xxx* alloys in T6-type tempers is often satisfactory. For rolled, extruded, or forged thick-section products, resistance in the short-transverse direction or across the flash plane of die forgings usually controls their use. Overaging stress-relief treatments that sacrifice some strength are very effective in providing high resistance to SCC in the copper-containing 7*xxx* alloys--7075, 7175, 7475, 7049, and 7050--in the T73, T736, and T74 tempers. Overaging of the premium strength 2*xx.x* casting alloys to T63 to T7 tempers provides good resistance to SCC, and 2219 in the T6 temper is similarly overaged with respect to strength to achieve high SCC resistance.

Medium-strength copper-free and low-copper alloys of the 7*xxx* group tend to be susceptible to SCC. Successful use of 7039, which has poor resistance, in armor-plate applications requires control of short-transverse stresses and weld overlays. Alloys 7016, 7021, and 7029 with copper contents up to 1% have good formability and finishing properties for automotive applications such as bumpers. Maximum SCC resistance is obtained by forming in the freshly quenched (W) temper followed by two-step aging. Casting alloys of the 7*xx.x* group have compositions similar to those of the aforementioned wrought alloys, and some SCC problems have occasionally been encountered in their applications.

Corrosion Fatigue. Fatigue strengths of aluminum alloys are lower in such corrosive environments as seawater and other salt solutions than in air, especially when evaluated by low-stress, long-duration tests. Such corrosive environments produce smaller reductions in fatigue strength in the more corrosion-resistant alloys, such as the 5*xxx* and 6*xxx* series, than in the less resistant alloys, such as 2*xxx* and 7*xxx* series.

Like SCC, corrosion fatigue requires the presence of water. In contrast to SCC, however, corrosion fatigue is not appreciably affected by test direction, because the fracture that results from this type of attack is predominantly transgranular.

Hydrogen Embrittlement. Only recently has it been determined that hydrogen embrittles aluminum. For many years, all environmental cracking of aluminum and aluminum alloys was represented as SCC; however, testing in specific hydrogen environments has revealed that aluminum is susceptible to hydrogen damage. Hydrogen damage in aluminum alloys may take the form of intergranular or transgranular cracking or blistering. Blistering is most often associated with the melting or heat treatment of aluminum, in which reaction with water vapor produces hydrogen. Blistering due to hydrogen is frequently associated with grain-boundary precipitates or the formation of small voids. Blister formation is different from that in ferrous alloys in that in aluminum it is more common to have a multitude of near-surface voids that coalesce to produce a large blister.

In a manner similar to the mechanism in iron-base alloys, hydrogen diffuses into the aluminum lattice and collects at internal defects. This occurs most frequently during annealing or solution treating in air furnaces prior to age hardening.

Most of the work on hydrogen embrittlement of aluminum has been on the 7*xxx* alloys; therefore, the full extent of hydrogen damage in aluminum alloys has not been determined and the mechanisms have not been established.

Erosion-Corrosion. In noncorrosive environments, such as high-purity water, the stronger aluminum alloys have the greatest resistance to erosion-corrosion because resistance is controlled almost entirely by the mechanical components of the system. In a corrosive environment, such as seawater, the corrosion component becomes the controlling factor; thus, resistance may be greater for the more corrosion-resistant alloys even though they are lower in strength. Corrosion inhibitors and cathodic protection have been used to minimize erosion-corrosion, impingement, and cavitation on aluminum alloys.

Corrosion at Joints

Joints fastened by mechanical fasteners--bolts, screws, cold headed rivets, and threaded connections--or by pressure or adhesive bonding require special attention to avoid galvanic effects, crevice corrosion, and assembly stresses in products susceptible to SCC. Methods of joining that involve heat--welding, brazing, and soldering--alter metallurgical structures of the parent material adjacent to the fusion zones and introduce composition differences between the joint proper and the parent metal. These can be a source of galvanic effects, particularly in heat treatable alloys, and are a factor of importance in selection of appropriate joining materials.

Alclad Products

In alclad aluminum products, the difference in solution potential between the core alloy and the cladding alloy is used to provide cathodic protection to the core. These products, primarily sheet and tube, consist of a core coated on one or both surfaces with a metallurgically bonded layer of an alloy that is anodic to the core alloy. The thickness of the cladding layer usually is less than 10% of the over-all thickness of the product. Cladding alloys generally are of the non-heat-treatable type, although, for higher strength, heat-treatable alloys sometimes are used. Composition relationships of core and cladding alloys generally are designed so that the cladding is 80 to 100 mV more anodic than the core. Table 6 lists several core alloy/cladding alloy combinations for common alclad products. Because of the cathodic protection provided by the cladding, corrosion progresses only to the core/cladding interface, and then spreads laterally. This is highly effective in eliminating perforation of thin products.

Table 6 Combination of aluminum alloys used in some alclad products

Core alloy	Cladding alloy
2014	6003 or 6053
2024	1230
2219	7072
3003	7072
3004	7072 or 7013
6061	7072
7075	7072, 7008, or 7011
7178	7072

Protective Coatings

Paints and other coatings are applied to aluminum alloy products for decorative as well as protective purposes. Almost any type of paint for metals (acrylic, alkyl, polyester, vinyl, etc.) is suitable; the performance of a particular paint on aluminum, when applied properly, is better than the performance on steel. As with any metal, surface preparation is important. Conversion coatings, of either the chromate or the phosphate type, are recommended for preparation of aluminum alloys. For milder environments, the paint can be applied to the conversion coating; for more aggressive environments such as those containing chlorides, a chromated primer should be applied first. Aluminum alloys are especially amenable to waterborne paints, which are being used increasingly because of environmental considerations. Many products precoated in a variety of colors for agricultural, industrial, and residential applications are available commercially.

Although more expensive, and restricted to in-plant application, anodized coatings provide excellent protection for aluminum alloys. They are also sometimes used as bases for paints. The many monumental buildings with outer walls of anodized aluminum alloys attest to the durability of these materials under conditions of weathering. Anodized coatings also provide a variety of colorations, most commonly shades of gray and bronze, produced by selection of both alloy and anodizing process.

Anodized coatings are produced by an electrolytic process in which the surface of an alloy that is made the anode is converted to aluminum oxide; this oxide is bound to the alloy as tenaciously as the natural oxide film but is much thicker. Coatings used to provide corrosion resistance range in thickness from 5 to 30 μm (0.2 to 1.2 mils); little or no additional protection is provided by thicker coatings. As with the alloys themselves, anodized coatings are not resistant to most environments with pH values outside the range from 4 to 9. Within this range, resistance to corrosion can be improved by an order of magnitude or more; in atmospheric weathering tests, the number of pits that developed in the base metal was found to decrease exponentially with coating thickness.

Introduction and Overview of Copper and Copper Alloys

Introduction

COPPER AND COPPER ALLOYS constitute one of the major groups of commercial metals, ranking third behind only iron/steel and aluminum in terms of production and consumption. Copper and copper alloys are widely used because of their excellent electrical and thermal conductivities, outstanding resistance to corrosion, and ease of fabrication, together with good strength and fatigue resistance. Copper offers the designer moderate levels of density (8.94 g/cm^3), elastic modulus (115 GPa, or 17×10^6 psi), and melting temperature (1083 °C, or 1981°F). It forms many useful alloys to provide a wide variety of engineering property combinations and is available in wrought, cast, and powder metallurgy(P/M) product forms. Wrought products include wire, flat products (plate, sheet, strip, and foil), tube, rod, bar, extrusions (shapes), and forgings. Castings can be produced by a variety of methods including sand (the most common casting method), continuous, centrifugal, die, investment, plaster, and permanent mold casting. Unique components, such as self-lubricating bearings and filters, are made by P/M methods. Structural parts, including high-strength oxide-dispersion-strengthened (ODS) copper alloys are also produced by P/M.

Characteristics of Copper and Copper Alloys

Property Characteristics

Conductivity. The electrical conductivity of commercially available pure copper, ~101% International Annealed Copper Standard (IACS), is second only to that of commercially pure silver (~103% IACS). Standard commercial copper is available with higher purity and, therefore, higher conductivity than what was available when the electrical resistivity value at 20 °C (70 °F) was picked to define the 100% level on the IACS scale in 1913. The thermal conductivity for copper is also high, 391 W/m · K (226 Btu/ft · h · °F), being directly related to the electrical conductivity through the Wiedemann-Franz relationship.

As with other metal systems, copper is intentionally alloyed to improve strength without unduly degrading ductility or workability. However, it should be recognized that additions of alloying elements also degrade electrical and thermal conductivity by various amounts depending on the alloying element, and the concentration and location in the microstructure (solid solution or dispersoid). The choice of alloy and condition is most often based on the trade off between strength and conductivity (Fig. 1). Alloying also changes the color from reddish brown to yellow(with zinc, as in brasses) and to metallic white or "silver" (with nickel, as in U.S. cupronickel coinage).

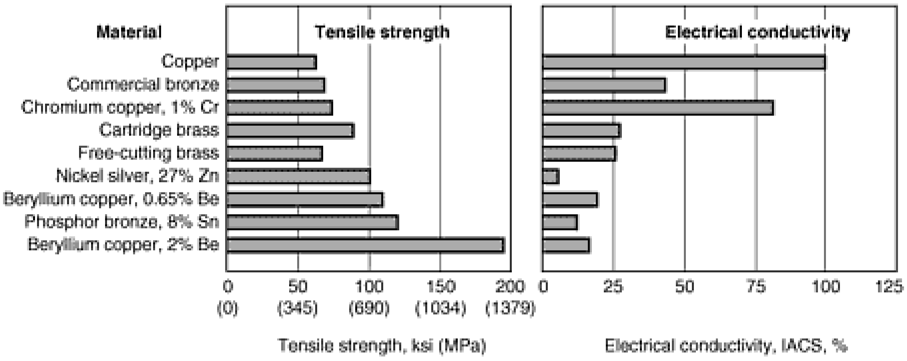


Fig. 1 Relationship between strength and electrical conductivity for copper and copper alloys

Corrosion Resistance. Copper is a noble metal, but, unlike gold and other precious metals, it can be attacked by common reagents and environments. Pure copper resists attack quite well under most corrosive conditions. Some copper alloys, however, have limited usefulness in certain environments because of hydrogen embrittlement or stress-corrosion cracking (SCC).

Hydrogen embrittlement is observed when tough pitch coppers, which are alloys containing cuprous oxide, are exposed to a reducing atmosphere. Most copper alloys are deoxidized and thus are not subject to hydrogen embrittlement.

Stress-corrosion cracking most commonly occurs in brass that is exposed to ammonia or amines. Brasses containing more than 15% Zn are the most susceptible. Copper and most copper alloys that either do not contain zinc or are low in zinc content generally are not susceptible to SCC. Because SCC requires both tensile stress and a specific chemical species to be present at the same time, removal of either the stress or the chemical species can prevent cracking. Annealing or stress relieving after forming alleviates SCC by relieving residual stresses. Stress relieving is effective only if the parts are not subsequently bent or strained in service; such operations reintroduce stresses and resensitize the parts to SCC.

Dealloying is another form of corrosion that affects zinc-containing copper alloys. In dealloying, the more active metal is selectively removed from an alloy, leaving behind a weak deposit of the more noble metal.

Copper-zinc alloys containing more than 15% Zn are susceptible to a dealloying process called dezincification. In the dezincification of brass, selective removal of zinc leaves a relatively porous and weak layer of copper and copper oxide. Corrosion of a similar nature continues beneath the primary corrosion layer, resulting in gradual replacement of sound brass by weak, porous copper. Unless arrested, dealloying eventually penetrates the metal, weakening it structurally and allowing liquids or gases to leak through the porous mass in the remaining structure.

A more detailed description of the corrosion resistance of copper is found in the article "Corrosion Characteristics of Copper and Copper Alloys" in this Section.

Fabrication Characteristics

Workability. Copper and copper alloys are readily cast into cake (slabs of pure copper, generally 200 mm thick and up to 8.5 m long, or 8 in. by 28 ft), billet, rod, or plate--suitable for subsequent hot or cold processing into plate, sheet, rod, wire, or tube--via all the standard rolling, drawing, extrusion, forging, machining, and joining methods. Copper and copper alloy tubing can be made by the standard methods of piercing and tube drawing as well as by the continuous induction welding of strip. Copper is hot worked over the temperature range 750 to 875 °C(1400 to 1600 °F), annealed between cold working steps over the temperature range 375 to 650 °C (700 to 1200 °F), and is thermally stress relieved usually between 200 and 350 °C (390 and 660 °F). Copper and copper alloys owe their excellent fabricability to the face-centered cubic crystal structure and the twelve available dislocation slip systems. Many of the applications of copper and copper alloys take advantage of the work-hardening capability of the material, with the cold processing deformation of the final forming steps providing the required strength/ductility for direct use or for subsequent forming of stamped components. Copper is easily processible to more than 95%reduction in area. The amount of cold deformation between softening anneals is usually restricted to 90% maximum to avoid excessive crystallographic texturing, especially in rolling of sheet and strip.

Although copper obeys the Hall-Petch relationship and grain size can be readily controlled by processing parameters, work hardening is the only strengthening mechanism used with pure copper. Whether applied by processing to shape and thickness, as a rolled strip or drawn wire, or by forming into the finish component, as an electrical connector, the amount of work hardening applied is limited by the amount of ductility required by the application. Worked copper can be recrystallized by annealing at temperatures as low as 250 °C (480 °F), depending on the prior degree or cold work and the time at temperature. While this facilitates processing, it also means that softening resistance during long-time exposures at moderately elevated temperatures can be a concern, especially in electrical and electronic applications where resistance (I^2R) heating is a factor.

Weldability. Copper and copper alloys are most frequently welded using gas tungsten arc welding (GTAW), especially for thin sections, because high localized heat input is important in materials with high thermal conductivity. In thicker sections, gas metal arc welding(GMAW) is preferred. The weldability varies among the different alloys for a variety of reasons, including the occurrence of hot cracking in the leaded(free-machining) alloys and unsound welds in alloys containing copper oxide. Tin and zinc both reduce the weldability of copper alloys. The presence in the alloy of residual phosphorus is beneficial to weldability, because it combines with absorbed oxygen, thereby preventing the formation of copper oxide in the weld. Resistance welding is also widely used, particularly in alloys with low-thermal conductivity. Most copper alloys can be brazed satisfactorily. Oxygen-bearing coppers can be subject to gassing and embrittlement, particularly in oxyacetylene welding.

Surface Finishes. For decorative parts, standard alloys in specific colors are readily available. Copper alloys can be polished and buffed to almost any desired texture and luster. They can be plated, coated with organic substances, or chemically colored to further extend the variety of available finishes.

The Copper Industry

The copper industry in the United States, broadly speaking, is composed of two segments: producers (mining, smelting, and refining companies) and fabricators (wire mills, brass mills, foundries, and powder plants). The end products of copper producers, the most important of which are refined cathode copper and wire rod, are sold almost entirely to copper fabricators. The end products of copper fabricators can be generally described as mill products and foundry products, and they consist of wire and cable, sheet, strip, plate, rod, bar, mechanical wire, tubing, forgings, extrusions, castings, and P/M shapes. These products are sold to a wide variety of industrial users. Certain mill products--chiefly wire, cable, and most tubular products--are used without further metalworking. On the other hand, most flat-rolled products, rod, bar, mechanical wire, forgings, and castings go through multiple metalworking, machining, finishing, and/or assembly operations before emerging as finished products.

Copper Producers. Figure 2 is a simplified flow chart of the copper industry. The box at the upper left represents mining companies, which remove vast quantities of low-grade material, mostly from open-pit mines, to extract copper from the crust of the earth. Approximately two tons of overburden must be removed along with each ton of copper ore. (The ratio of overburden to ore is sometimes as high as 5 to 1.) The ore itself averages only ~0.7% Cu.

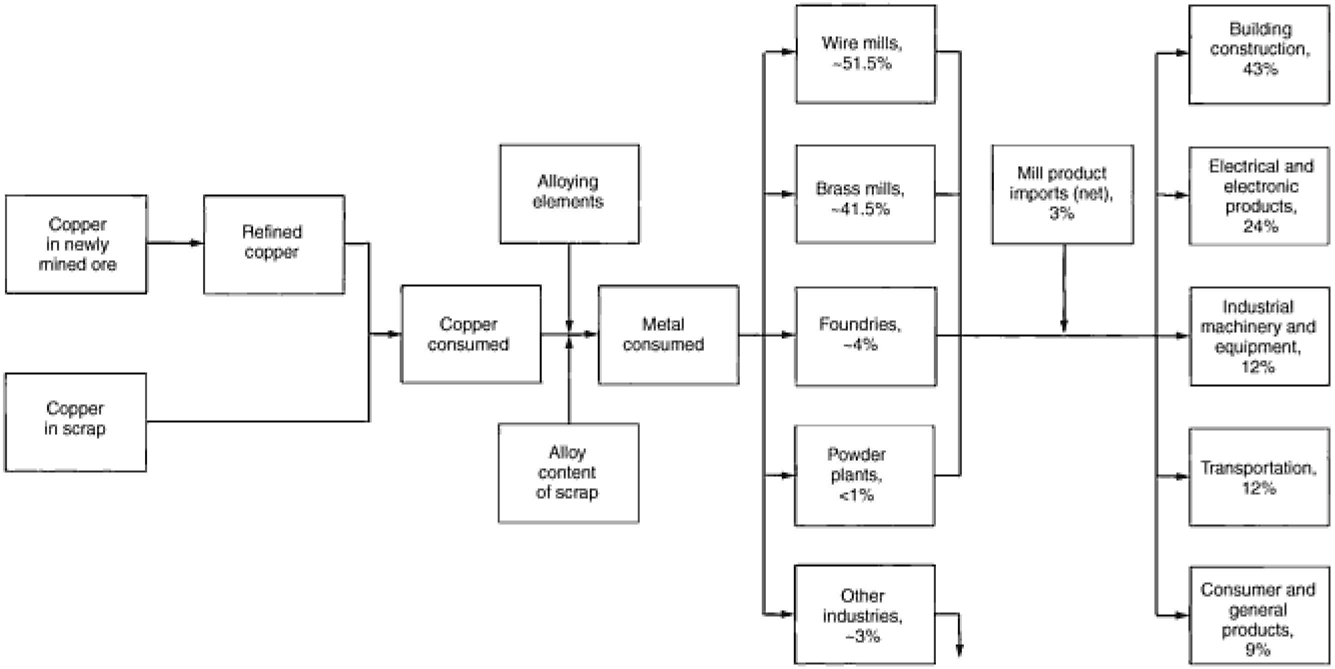

Copper in newly mined ore
Refined copper
Copper in scrap
Copper consumed
Alloying elements
Alloy content of scrap
Metal consumed
Wire mills, ~51.5%
Brass mills, ~41.5%
Foundries, ~4%
Powder plants, <1%
Other industries, ~3%
Mill product imports (net), 3%
Building construction, 43%
Electrical and electronic products, 24%
Industrial machinery and equipment, 12%
Transportation, 12%
Consumer and general products, 9%

Fig. 2 Copper supply and consumption in the United States for 1996. See text for details. Source: Copper Development Association Inc.

Copper ore normally is crushed, ground, and concentrated, usually by flotation, to produce a beneficiated ore containing $\sim$25% Cu. The ore concentrates are then reduced to the metallic state, most often by a pyrometallurgical process. Traditionally, the concentrated ore is processed in a primary smelting reactor, such as a reverberatory furnace, to produce a copper sulfide-iron sulfide matte containing up to 60% Cu. Reverberatory technology is rapidly being replaced by oxygen/flash smelting, which greatly reduces the volume of off gases. Sulfuric acid is manufactured from the sulfur dioxide contained in these off gases and is an important coproduct of copper smelting. The matte is oxidized in a converter to transform the iron sulfides to iron oxides, which separate out in a slag, and to reduce the copper sulfide to blister copper, which contains at least 98.5% Cu. Current technology combines the converter step with the preceding smelting step. Fire refining of blister copper then removes most of the oxygen and other impurities, leaving a product at least 99.5% pure, which is cast into anodes. Finally, most anode copper is electrolytically refined, usually to a purity of at least 99.95%.

The resulting cathodes are the normal end product of the producer companies and are a common item of commerce. In recent years, many producers have installed continuous casting rod mills to directly convert cathode copper to wire rod(typically, 8 mm or $\frac{5}{16}$ in., in diameter), which is the feed material for the wire mills. Primary producers may also convert the cathode to cakes or billets of copper for sale to brass mills.

Hydrometallurgical processing is an increasingly important alternative to pyrometallurgy, particularly for nonsulfide ores such as oxides, silicates, and carbonates. In this process, weak acid is percolated through ore or waste dumps of rejected materials. Copper is leached out and recovered from the pregnant leach liquor, most often by solvent extraction, to produce an electrolyte suitable for electrowinning. In electrowinning, copper is extracted electrolytically in much the same was as anode copper is electrorefined. Copper extracted by electrowinning is equal in quality to that produced by electrolytic refining.

The box at the lower left in Fig. 2 represents the portion of the copper supply provided by scrap. In recent years, well over half the copper consumed in the United States has been derived from recycled scrap, and this percentage has grown somewhat over the last three decades. Approximately 55% of this scrap has been new scrap, such as turnings from screw-machined rod, as opposed to old scrap, such as used electrical cable or auto radiators. Scrap recycled within a particular plant or company (runaround scrap) is not included in these statistics. About one-third of the scrap recycled in the United States is fed into the smelting or refining stream and quickly loses any identity. The remainder is consumed directly by brass mills; by ingot makers, whose main function is to process scrap into alloy ingot for use by foundries; by foundries themselves; by powder plants; and by others, such as the chemical, aluminum, and steel industries.

The box labeled "copper consumed" in Fig. 2 represents the total tonnage of refined copper plus the copper content of scrap consumed directly by fabricator companies. The various alloying elements used in producing copper alloys and the alloy content of the directly consumed scrap are added to obtain the total metal consumed by copper fabricators and other industries.

Copper Fabricators. The four classes of copper fabricators together account for ~97% of the total copper(including alloying metal) consumed each year in the United States (Fig. 2). Other industries, such as steel, aluminum, and chemical producers, consume the remaining 3%.

The share of metal consumed by wire rod mills has grown sharply over the last 30 years to the present (1996) level of ~51.5%; consumption by brass mills has dropped to 41.5%. Foundries account for about 4% of fabricated mill products, and powder plants use less than 1% of the U.S. supply of copper.

Wire mill products are destined for use as electrical conductors. Starting with wire rod, these mills cold draw the material (with necessary anneals)to final dimensions through a series of dies. The individual wires can be stranded and normally are insulated before being gathered into cable assemblies.

Brass mills melt and alloy feedstock to make strip, sheet, plate, tube, rod, bar, mechanical wire, forgings, and extrusions. Less than half the copper input to brass mills is refined; the rest is scrap. Fabricating processes such as hot rolling, cold rolling, extrusion, and drawing are employed to convert the melted and cast feedstock into mill products.

Approximately 45% of the output of U.S. brass mills is unalloyed copper and high-copper alloys, chiefly in such forms as plumbing and air conditioning tube, busbar and other heavy-gage current-carrying flat products, and roofing sheet. Copper alloys make up the remaining 55%. Free-cutting brass rod, which exhibits outstanding machinability and good corrosion resistance, and brass strip, which has high strength, good corrosion resistance, excellent formability, and good electrical properties, together constitute ~80% of the total tonnage of copper alloys shipped from U.S. brass mills. Other alloy types of major commercial significance include tin bronzes (phosphor bronzes), which are noted for their excellent cold-forming behavior and strength; tin brasses, known for outstanding corrosion resistance; copper-nickels, which are strong and particularly resistant to seawater; nickel silvers, which combine a silvery appearance with good formability and corrosion resistance; beryllium-coppers, which provide outstanding strength when hardened; and aluminum bronzes, which have high strength along with good resistance to oxidation, chemical attack, and mechanical abrasion.

Foundries use prealloyed ingot, scrap, and virgin metal as raw materials. Their chief products are shaped castings for many different industrial and consumer goods, the most important of which are plumbing products and industrial valves. Centrifugal and continuously cast products find major application as bearings, cylinders, and other symmetrical components. Powder plants produce powder and flake for further fabrication into powder metallurgy parts, chiefly small sintered porous bronze bearings.

Markets and Applications. The five major market categories shown at the far right in Fig. 2 constitute the chief customer industries of the copper fabricators. Of the chief customer industries, the largest is building construction, which purchases large quantities of electrical wire, tubing, and parts for building hardware and for electrical, plumbing, heating, and air-conditioning systems. The second largest category is electrical and electronic products, including those for telecommunications, electronics, wiring devices, electric motors, and power utilities. The industrial machinery and equipment category includes industrial valves and fittings; industrial, chemical, and marine heat exchangers; and various other types of heavy equipment, off-road vehicles, and machine tools. Transportation applications include road vehicles, railroad equipment, and aircraft parts;automobile radiators and wiring harnesses are the most important products in this category. Finally, consumer and general products include electrical appliances, fasteners, ordnance, coinage, and jewelry.

In service in these five market areas, copper and copper alloys fulfill five primary functions: electrical conductivity, corrosion resistance, heat transfer, structural capability, and aesthetics. The analysis of the consumption of copper for 1996 by these primary functions reveals the following distribution:

Function	Consumption	
	lb × 10^6	**%**
Electrical	4401	58
Corrosion resistance	1650	21.7
Heat transfer	947	12.5
Structural	486	6.4
Aesthetics	107	1.4
Total	**7591**	**100**

Source: Copper Development Association Inc.

Table 1 is a more detailed listing of the largest markets for copper and copper alloys in the United States.

Table 1 Leading copper markets in the United States in 1996

Application	Consumption	
	lb × 10^6	**%**
Building wire	1215	16
Plumbing and heating	1147	15.1
Air conditioning and commercial refrigeration	671	8.8
Power utilities	647	8.5
Telecommunications	544	7.2
Automotive (electrical)	511	6.7
In-plant equipment	500	6.6
Electronics	409	5.4

Automotive (nonelectrical)	276	3.6
Industrial valves and fittings	239	3.2
Lighting and wiring devices	231	3.1
All other	1201	15.8
Total	**7591**	**100**

Source: Copper Development Association Inc.

Alloy and Temper Designation Systems

Alloy Designations. In North America, the accepted designation for copper alloys is part of the Unified Numbering System (UNS). Under the UNS system, the identifiers of copper alloys take the form of five-digit codes preceded by the letter "C" (for copper). The five-digit codes are based on, and supersede, an older three-digit system administered by the Copper Development Association Inc. (CDA). The UNS designations for copper alloys are simply two-digit extensions of the CDA numbers. For example, the leaded brass (85Cu-5Sn-5Pb-5Zn, or 85-5-5-5), once known as CDA Alloy No. 836, became UNS C83600.

Table 2 summarizes the standard UNS designation system. As this table indicates, wrought alloys are assigned UNS numbers from C10000 through C79999; cast alloys are numbered from C80000 through C99999.

Table 2 Generic classification of copper alloys

Generic name	UNS No.	Composition
Wrought alloys		
Coppers	C10100-C15760	>99% Cu
High-copper alloys	C16200-C19600	>96% Cu
Brasses	C20500-C28580	Cu-Zn
Leaded brasses	C31200-C38590	Cu-Zn-Pb
Tin brasses	C40400-C49080	Cu-Zn-Sn-Pb
Phosphor bronzes	C50100-C52400	Cu-Sn-P
Leaded phosphor bronzes	C53200-C54800	Cu-Sn-Pb-P
Copper-phosphorus and copper-silver-phosphorus alloys	C55180-C55284	Cu-P-Ag

Aluminum bronzes	C60600-C64400	Cu-Al-Ni-Fe-Si-Sn
Silicon bronzes	C64700-C66100	Cu-Si-Sn
Other copper-zinc alloys	C66400-C69900	. . .
Copper-nickels	C70000-C79900	Cu-Ni-Fe
Nickel silvers	C73200-C79900	Cu-Ni-Zn
Cast alloys		
Coppers	C80100-C81100	>99% Cu
High-copper alloys	C81300-C82800	>94% Cu
Red and leaded red brasses	C83300-C85800	Cu-Zn-Sn-Pb (75-89% Cu)
Yellow and leaded yellow brasses	C85200-C85800	Cu-Zn-Sn-Pb (57-74% Cu)
Manganese bronzes and leaded manganese bronzes	C86100-C86800	Cu-Zn-Mn-Fe-Pb
Silicon bronzes, silicon brasses	C87300-C87900	Cu-Zn-Si
Tin bronzes and leaded tin bronzes	C90200-C94500	Cu-Sn-Zn-Pb
Nickel-tin bronzes	C94700-C94900	Cu-Ni-Sn-Zn-Pb
Aluminum bronzes	C95200-C95810	Cu-Al-Fe-Ni
Copper-nickels	C96200-C96800	Cu-Ni-Fe
Nickel silvers	C97300-C97800	Cu-Ni-Zn-Pb-Sn
Leaded coppers	C98200-C98800	Cu-Pb
Special alloys	C99300-C99750	. . .

Temper Designations. Copper alloys are also described by their *tempers*, which are terms that define metallurgical condition, heat treatment, and/or casting method. The temper designations for wrought copper and copper alloys were traditionally specified on the basis of cold reduction imparted by rolling or drawing. This scheme related the nominal temper designations to the amount of reduction stated in Brown & Sharpe (B & S) gage numbers for rolled sheet and drawn wire. Heat-treatable alloys and product forms such as rod, tube, extrusions, and castings were not readily described by this system. To remedy this situation, ASTM B 601, "Standard Practice for Temper Designations for Copper and Copper Alloys--Wrought and Cast," was developed. This standard established an alphanumeric code that can be assigned to each of the standard descriptive temper designations (Table 3).

Table 3 ASTM B 601 temper designation codes for copper and copper alloys

Temper designation	Temper name or material condition
Cold-worked tempers[(a)]	
H00	$\frac{1}{8}$ hard
H01	$\frac{1}{4}$ hard
H02	$\frac{1}{2}$ hard
H03	$\frac{3}{4}$ hard
H04	Hard
H06	Extra hard
H08	Spring
H10	Extra spring
H12	Special spring
H13	Ultra spring
H14	Super spring
Cold-worked tempers[(b)]	
H50	Extruded and drawn
H52	Pierced and drawn
H55	Light drawn; light cold rolled

H58	Drawn general purpose
H60	Cold heading; forming
H63	Rivet
H64	Screw
H66	Bolt
H70	Bending
H80	Hard drawn
H85	Medium-hard-drawn electrical wire
H86	Hard-drawn electrical wire
H90	As finned
Cold-worked and stress-relieved tempers	
HR01	H01 and stress relieved
HR02	H02 and stress relieved
HR04	H04 and stress relieved
HR08	H08 and stress relieved
HR10	H10 and stress relieved
HR20	As finned
HR50	Drawn and stress relieved
Cold-rolled and order-strengthened temper(c)	
HT04	H04 and order heat treated
HT08	H08 and order heat treated

As-manufactured tempers	
M01	As-sand cast
M02	As-centrifugal cast
M03	As-plaster cast
M04	As-pressure die cast
M05	As-permanent mold cast
M06	As-investment cast
M07	As-continuous cast
M10	As-hot forged and air cooled
M11	As-forged and quenched
M20	As-hot rolled
M30	As-hot extruded
M40	As-hot pierced
M45	As-hot pierced and rerolled
Annealed tempers(d)	
O10	Cast and annealed (homogenized)
O11	As-cast and precipitation heat treated
O20	Hot forged and annealed
O25	Hot rolled and annealed
O30	Hot extruded and annealed
O31	Extruded and precipitation heat treated

O40	Hot pierced and annealed
O50	Light annealed
O60	Soft annealed
O61	Annealed
O65	Drawing annealed
O68	Deep-drawing annealed
O70	Dead-soft annealed
O80	Annealed to temper, $\frac{1}{8}$ hard
O81	Annealed to temper, $\frac{1}{4}$ hard
O82	Annealed to temper, $\frac{1}{2}$ hard
Annealed tempers(e)	
OS005	Average grain size, 0.005 mm
OS010	Average grain size, 0.010 mm
OS015	Average grain size, 0.015 mm
OS025	Average grain size, 0.025 mm
OS035	Average grain size, 0.035 mm
OS050	Average grain size, 0.050 mm
OS060	Average grain size, 0.060 mm
OS070	Average grain size, 0.070 mm
OS100	Average grain size, 0.100 mm

OS120	Average grain size, 0.120 mm
OS150	Average grain size, 0.150 mm
OS200	Average grain size, 0.200 mm
Solution-treated temper	
TB00	Solution heat treated
Solution-treated and cold-worked tempers	
TD00	TB00 cold worked to $\frac{1}{8}$ hard
TD01	TB00 cold worked to $\frac{1}{4}$ hard
TD02	TB00 cold worked to $\frac{1}{2}$ hard
TD03	TB00 cold worked to $\frac{3}{4}$ hard
TD04	TB00 cold worked to full hard
Solution-treated and precipitation-hardened temper	
TF00	TB00 and precipitation hardened
Cold-worked and precipitation-hardened tempers	
TH01	TD01 and precipitation hardened
TH02	TD02 and precipitation hardened
TH03	TD03 and precipitation hardened
TH04	TD04 and precipitation hardened
Precipitation-hardened and cold-worked tempers	

TL00	TF00 cold worked to $\frac{1}{8}$ hard
TL01	TF00 cold worked to $\frac{1}{4}$ hard
TL02	TF00 cold worked to $\frac{1}{2}$ hard
TL04	TF00 cold worked to full hard
TL08	TF00 cold worked to spring
TL10	TF00 cold worked to extra spring
Mill-hardened tempers	
TM00	AM
TM01	$\frac{1}{4}$ HM
TM02	$\frac{1}{2}$ HM
TM04	HM
TM06	XHM
TM08	XHMS
Quench-hardened tempers	
TQ00	Quench hardened
TQ50	Quench hardened and temper annealed
TQ55	Quench hardened and temper annealed, cold drawn and stress relieved
TQ75	Interrupted quench hardened
Precipitation-hardened, cold-worked, and thermal-stress-relieved tempers	

TR01	TL01 and stress relieved
TR02	TL02 and stress relieved
TR04	TL04 and stress relieved
Solution-treated and spinodal-heat-treated temper	
TX00	Spinodal hardened
Tempers of welded tubing[(f)]	
WH00	Welded and drawn to $\frac{1}{8}$ hard
WH01	Welded and drawn to $\frac{1}{4}$ hard
WH02	Welded and drawn to $\frac{1}{2}$ hard
WH03	Welded and drawn to $\frac{3}{4}$ hard
WH04	Welded and drawn to full hard
WH06	Welded and drawn to extra hard
WM00	As welded from H00 ($\frac{1}{8}$ -hard) strip
WM01	As welded form H01 ($\frac{1}{4}$ -hard) strip
WM02	As welded from H02 ($\frac{1}{2}$ -hard) strip
WM03	As welded from H03 ($\frac{3}{4}$ -hard) strip
WM04	As welded from H04 (full-hard) strip
WM06	As welded from H06 (extra-hard) strip
WM08	As welded from H08 (spring) strip

WM10	As welded from H10 (extra-spring) strip
WM15	WM50 and stress relieved
WM20	WM00 and stress relieved
WM21	WM01 and stress relieved
WM22	WM02 and stress relieved
WM50	As welded from annealed strip
WO50	Welded and light annealed
WR00	WM00; drawn and stress relieved
WR01	WM01; drawn and stress relieved
WR02	WM02; drawn and stress relieved
WR03	WM03; drawn and stress relieved
WR04	WM04; drawn and stress relieved
WR06	WM06; drawn and stress relieved

(a) Cold-worked tempers to meet standard requirements based on cold rolling or cold drawing.

(b) Cold-worked tempers to meet standard requirements based on temper names applicable to specific products.

(c) Tempers produced by controlled amounts of cold work followed by a thermal treatment to produce order strengthening.

(d) Annealed to meet specific mechanical property requirements.

(e) Annealed to meet prescribed nominal average grain size.

(f) Tempers of fully finished tubing that has been drawn or annealed to produce specified mechanical properties or that has been annealed to produce a prescribed nominal average grain size are commonly identified by the appropriate H, O, or OS temper designation.

International Alloy Designations. A common designation system used within the International Organization for Standardization (ISO) is a compositional system described in ISO 1190 Part 1, based on the element symbols and the descending order of magnitude of alloying elements. For example, a leaded brass containing 60% Cu and 2%Pb is designated CuZn38Pb2. Because this system is unwieldy when used to describe complex alloys, a European numbering system has been formulated by the ComitéEuropéen de Normalisation (CEN). CEN/TC 132 describes a six-digit alpha-numerical system. The first letter, "C," indicates a copper alloy. A second letter was introduced to indicate the material state (i.e., W for a wrought material, C for castings, and M for master alloys). Three numbers are then used to identify the material, and a final third letter is used to identify the classification of individual copper material groups and to enlarge the capacity of the designation system. Table 4 shows the preferred number ranges and letters allocated by the CEN numbering system to the different copper alloy groups. Table 5 cross references some ISO and CEN designations.

Table 4 CEN European numbering system for copper and copper alloys, showing the preferred number ranges and letters allocated to the different material groups

Material groups	Number ranges available for positions 3, 4, and 5	Final letter, designating material group	Number range allocated to materials preferred by CEN
Copper	001-999	A	001-049A
	001-999	B	050-099B
Miscellaneous copper alloys	001-999	C	100-149C
	001-999	D	150-199D
	001-999	E	200-249E
	001-999	F	250-299F
Copper-aluminum alloys	001-999	G	300-349G
Copper-nickel alloys	001-999	H	350-399H
Copper-nickel-zinc alloys	001-999	J	400-449J
Copper-tin alloys	001-999	K	459-499K
Copper-zinc-alloys, binary	001-999	L	500-549L
	001-999	M	550-599M
Copper-zinc-lead alloys	001-999	N	600-649N
	001-999	P	650-699P

Copper-zinc alloys, complex	001-999	R	700-749R
			750-799S
Copper material not standardized by CEN/TC 133	800-999	A-S(a)	800-999(a)

(a) Letter as appropriate for the material group

Table 5 Selected ISO copper and copper alloys cross referenced to CEN numbers

Materials	Material designations	
	ISO symbols	**CEN numbers**
Coppers	Cu-ETP	CW 004A
	Cu-OF	CW 008A
Wrought brasses	CuZn37	CW 508L
	CuZn39Pb3	CW 614N
	CuZn20Al2As	CW 702R
	CuZn40Mn1Pb1AlFeSn	CW 721R
Other wrought alloys	CuNi2Si	CW 111C
	CuAl10Fe1	CW 305G
	CuNi30Mn1Fe	CW 354H
Cast alloys	CuZn33Pb2-GB	CB 750S
	CuZn33Pb2-GS	CC 750S
	CuSn12-GB	CB 483K
	CuSn12-GS	CC 483K
Master alloys	CuAl50 (A)-M	CM 344G

	CuCr10-M	CM 204E
	CuS20-M	CM 220E

Introduction and Overview of Copper and Copper Alloys

Wrought Copper Alloys

The purpose of adding alloying elements to copper is to optimize the strength, ductility (formability), and thermal stability, without inducing unacceptable loss in fabricability, electrical/thermal conductivity, or corrosion resistance. Copper alloys show excellent hot and cold ductility, although usually not to the same degree as the unalloyed parent metal. Even alloys with large amounts of solution-hardening elements--zinc, aluminum, tin, and silicon--that show rapid work hardening are readily commercially processed beyond 50% cold work before a softening anneal is required to permit additional processing. The amount of cold working and the annealing parameters must be balanced to control grain size and crystallographic texturing. These two parameters are controlled to provide annealed strip products at finish gage that have the formability needed in the severe forming and deep drawing commonly done in commercial production of copper, brass, and other copper alloy hardware and cylindrical tubular products.

Table 6 lists chemical compositions of wrought coppers and copper alloys. Typical mechanical properties for these materials are given in Table 7.

Table 6 Chemical compositions of wrought copper and copper alloys

Composition values are given as maximum percentages, unless shown as a range or maximum.

Coppers										
Copper No.	**Designation**	**Description**	**Composition, wt%**							
			Cu, min, (including Ag), %	**Ag, min**		**As**	**Sb**	**P**	**Te**	**Other named elements**
				%	**Troy oz**					
C10100	OFE	Oxygen-free electronic	99.99(b)	. . .	. . .	0.0005	0.0004	0.0003	0.0002	(c)
C10200(a)	OF	Oxygen free	99.95	. . .	. . .	. . .	. . .	. . .	. . .	0.0010 O
C10300	OFXLP	. . .	99.95(d)	. . .	. . .	. . .	. . .	0.001-0.005	. . .	. . .
C10400(a)	OFS	Oxygen-free with Ag	99.95	0.027	8	. . .	. . .	. . .	. . .	. . .
C10500(a)	OFS	Oxygen-free with Ag	99.95	0.034	10	. . .	. . .	. . .	. . .	. . .

C10700	OFS	Oxygen-free with Ag	99.95	0.085	25	. . .	. . .	. . .	. . .	. . .
C10800	OFLP	. . .	99.95(d)	. . .	. . .	. . .	. . .	0.005-0.012	. . .	. . .
C10920	. . .	. . .	99.90	. . .	. . .	. . .	. . .	. . .	. . .	0.02 O
C10930	. . .	. . .	99.90	0.044	13	. . .	. . .	. . .	. . .	0.02 O
C10940	. . .	. . .	99.90	0.085	25	. . .	. . .	. . .	. . .	0.02 O
C11000(a)	ETP	Electrolytic tough pitch	99.90	. . .	. . .	. . .	. . .	. . .	. . .	(e)
C11010(a)	RHC	Remelted high conductivity	99.90	. . .	. . .	. . .	. . .	. . .	. . .	(e)
C11020(a)	FRHC	Fire-refined high conductivity	99.90	. . .	. . .	. . .	. . .	. . .	. . .	(e)
C11030(a)	CRTP	Chemically refined tough pitch	99.90	. . .	. . .	. . .	. . .	. . .	. . .	(e)
C11040(a)	. . .	. . .	99.90	. . .	. . .	0.0005	0.0004	. . .	0.0002	(f)
C11100(a)	. . .	Electrolytic tough pitch, anneal resistant	99.90	. . .	. . .	. . .	. . .	. . .	. . .	(g)
C11300(a)	STP	Tough pitch with Ag	99.90	0.027	8	. . .	. . .	. . .	. . .	(e)
C11400(a)	STP	Tough pitch with Ag	99.90	0.034	10	. . .	. . .	. . .	. . .	(e)
C11500(a)	STP	Tough pitch with Ag	99.90	0.054	16	. . .	. . .	. . .	. . .	(e)
C11600(a)	STP	Tough pitch with Ag	99.90	0.085	25	. . .	. . .	. . .	. . .	(e)
C11700	. . .	. . .	99.9(h)	. . .	. . .	. . .	. . .	0.04	. . .	0.004-0.02B
C12000	DLP	Phosphorus-deoxidized, low	99.90	. . .	. . .	. . .	. . .	0.004-	. . .	. . .

		residual phosphorus						0.012		
C12100	. . .	. . .	99.90	0.014	4	. . .	. . .	0.005-0.012	. . .	. . .
C12200[i]	DHP	Phosphorus-deoxidized high residual phosphorus	. . .	99.9	. . .	. . .	. . .	. . .	0.015-0.040	. . .
C12210	. . .	. . .	99.90	. . .	. . .	. . .		0.015-0.025	. . .	. . .
C12220	. . .	. . .	99.9	. . .	. . .	. . .	. . .	0.040-0.065	. . .	. . .
C12300	. . .	. . .	99.90	. . .	. . .	. . .	. . .	0.015-0.040	. . .	. . .
C12900	FRSTP	Fire-refined tough pitch with Ag	99.88	0.054	16	0.012	0.003	. . .	0.025[j]	0.050Ni 0.003Bi 0.004Pb
C14180	. . .	. . .	99.90	. . .	. . .	. . .	. . .	0.075	. . .	0.02Pb 0.01Al
C14181	. . .	. . .	99.90	. . .	. . .	. . .	. . .	0.002	. . .	0.002Cd 0.005C 0.002Pb 0.002Zn
C14200	DPA	Phosphorus-deoxidized arsenical	99.4	. . .	. . .	0.15-50	. . .	0.015-0.040	. . .	. . .
C14300	. . .	Cadmium copper, deoxidized	99.90[k]	. . .	. . .	. . .	. . .	. . .	. . .	0.05-0.15Cd
C14410	. . .	. . .	99.90[l]	. . .	. . .	. . .	. . .	0.005-0.020	. . .	0.05Fe 0.05Pb 0.10-0.20Sn
C14415	. . .	. . .	99.96[l]	. . .	. . .	. . .	. . .	. . .	. . .	0.10-0.15Sn
C14420	. . .	. . .	99.90[m]	. . .	. . .	. . .	. . .	. . .	0.005-0.05	0.04-0.15Sn
C14500[n]	. . .	Tellurium bearing	99.90[m]	. . .	. . .	. . .	. . .	0.004-0.012	0.40-0.7	. . .

C14510	. . .	Tellurium bearing	99.90(m)	. . .	. . .	. . .	. . .	0.010-0.030	0.30-0.7	0.05Pb
C14520	DPTE	Phosphorus-deoxidized, tellurium-bearing	99.40(m)	. . .	. . .	. . .	. . .	0.004-0.020	0.40-0.7	. . .
C14530	. . .	. . .	99.90(j)(l)	. . .	. . .	. . .	. . .	0.001-0.010	0.003-0.023(j)	0.003-0.023Sn
C14700	. . .	Sulfur-bearing	99.90(n)	. . .	. . .	. . .	. . .	0.002-0.005	. . .	0.20-0.50S
C15000	. . .	Zirconium copper	99.80	. . .	. . .	. . .	. . .	. . .	. . .	0.10-0.20Zr
C15100	. . .	. . .	99.82	. . .	. . .	. . .	. . .	. . .	. . .	0.005Al 0.005Mn 0.05-0.15Zr
C15500	. . .	. . .	99.75	0.027-0.10	8-30	. . .	. . .	0.040-0.080	. . .	0.08-0.13Mg

Copper No.	Composition, wt%				
	Cu (including Ag), min	**Al(o)**	**Fe**	**Pb**	**O(o)**
C15715	99.62	0.13-0.17	0.01	0.01	0.12-0.19
C15720	99.52	0.18-0.22	0.01	0.01	0.16-0.24
C15725	99.43	0.23-0.27	0.01	0.01	0.20-0.28
C15760	98.77	0.58-0.62	0.01	0.01	0.52-0.59

Alloys C16200-C19150(high-copper alloys)

Copper alloy No.	**Previous tradename**	**Composition, wt%**									
		Cu (including Ag)	**Fe**	**Sn**	**Ni**	**Co**	**Cr**	**Si**	**Be**	**Pb**	**Other named elements**
C16200	Cadmium copper	bal(p)	0.02	. . .	. . .	. . .	. . .	. . .	. . .	. . .	0.7-1.2Cd

C16500	. . .	bal(p)	0.02	0.50-0.7	. . .	. . .	. . .	. . .	. . .	. . .	0.6-1.0Cd
C17000	Beryllium copper	bal(p)	(q)	. . .	(q)	(q)	. . .	0.20	1.60-1.79	. . .	0.20Al
C17200	Beryllium copper	bal(p)	(q)	. . .	(q)	(q)	. . .	0.20	1.80-2.00	0.02	0.20Al
C17300	. . .	bal(p)	(q)	. . .	(q)	(q)	. . .	0.20	1.80-2.00	0.20-0.6	0.20Al
C17410	. . .	bal(p)	0.20	. . .	. . .	0.35-0.6	. . .	0.20	0.15-0.50	. . .	0.20Al
C17500	Beryllium copper	bal(p)	0.10	. . .	. . .	2.4-2.7	. . .	0.20	0.40-0.70	. . .	0.20Al
C17510	. . .	bal(p)	0.10	. . .	1.4-2.2	0.30	. . .	0.20	0.20-0.6	. . .	0.20Al
C18000	. . .	bal(p)	0.15	. . .	1.8-3.0(r)	. . .	0.10-0.8	0.40-0.8	. . .	. . .	. . .
C18030	. . .	bal(s)	. . .	0.08-0.12	. . .	. . .	0.10-0.20	. . .	. . .	. . .	0.005-0.015P
C18040	. . .	bal(n)	. . .	0.20-0.30	. . .	. . .	0.25-0.35	. . .	. . .	. . .	0.005-0.015P 0.05-0.15Zn
C18050	. . .	bal(t)	. . .	. . .	. . .	. . .	0.05-0.15	. . .	. . .	. . .	0.005-0.015Te
C18070	. . .	99.0(t)	. . .	. . .	. . .	. . .	0.15-0.40	0.02-0.07	. . .	. . .	0.01-0.40Ti
C18090	. . .	96.0 min(cc)	. . .	0.50-1.2	0.30-1.2	. . .	0.20-1.0	. . .	. . .	. . .	0.15-8Ti
C18100	. . .	98.7 min(p)	. . .	. . .	. . .	. . .	0.40-1.2	. . .	. . .	. . .	0.03-0.06Mg 0.08-0.20Zr
C18135	. . .	bal(p)	. . .	. . .	. . .	. . .	0.20-0.6	. . .	. . .	. . .	0.20-0.6Cd
C18140	. . .	bal(p)	. . .	. . .	. . .	. . .	0.15-0.45	0.005-0.05	. . .	. . .	0.05-0.25Zr

C18150	. . .	bal(u)	. . .	. . .	. . .	. . .	0.50-1.5	. . .	. . .	. . .	0.05-0.25Zr
C18200	Chromium copper	bal(p)	0.10	. . .	. . .	. . .	0.06-1.2	0.10	. . .	0.05	. . .
C18400	Chromium copper	bal(p)	0.15	. . .	. . .	. . .	0.40-1.2	0.10	. . .	. . .	0.005As 0.005Ca 0.05Li 0.05P 0.7Zn
C18700	. . .	bal(p)	. . .	. . .	. . .	. . .	. . .	. . .	. . .	0.8-1.5	. . .
C18900	. . .	bal(p)	. . .	0.6-0.9	. . .	. . .	. . .	0.15-0.40	. . .	0.02	0.05P 0.01Al 0.10-0.30Mn 0.10Zn
C18980	. . .	98.0(p)	. . .	1.0	. . .	. . .	. . .	0.50	. . .	0.02	0.50Mn 0.15P
C18990	. . .	bal(s)	. . .	1.8-2.2	. . .	. . .	0.10-0.20	. . .	. . .	. . .	0.005-0.015P
C19000	. . .	bal(p)	0.10	. . .	0.9-1.3	. . .	. . .	. . .	. . .	0.05	0.8Zn 0.015-0.35P
C19010	. . .	bal(p)	. . .	. . .	0.8-1.8	. . .	. . .	0.15-0.35	. . .	. . .	0.01-0.05P
C19015	. . .	bal(t)	. . .	. . .	0.50-2.4	. . .	. . .	0.10-0.40	. . .	. . .	0.02-0.20P 0.02-0.15Mg
C19020	. . .	bal(t)	. . .	0.30-0.9	0.50-3.0	. . .	. . .	. . .	. . .	. . .	0.01-0.20P 0.35Mn+Si
C19030	. . .	bal(u)	0.10	1.0-1.5	1.5-2.0	. . .	. . .	. . .	. . .	0.02	0.01-0.03P
C19100	. . .	bal(p)	0.20	. . .	0.9-1.3	. . .	. . .	. . .	. . .	0.10	0.50Zn 0.35-0.6Te 0.15-0.35P
C19150	. . .	bal(p)	0.05	0.05	0.8-1.2	. . .	. . .	. . .	. . .	0.50-1.0	0.15-0.35P

Alloys C19200-C19900(high-copper alloys)

Copper alloy No.	**Composition, wt%**							
	Cu	**Fe**	**Sn**	**Zn**	**Al**	**Pb**	**P**	**Other named elements**
C19200	98.5 min(t)	0.8-1.2	. . .	0.20	. . .	. . .	0.01-0.04	. . .
C19210	bal(t)	0.05-0.15	. . .	. . .	. . .	. . .	0.025-0.040	. . .
C19220	bal(t)	0.10-0.30	0.05-0.10	. . .	. . .	. . .	0.03-0.07	0.005-0.015B 0.10-0.25Ni
C19260	98.5 min(s)	0.40-0.8	. . .	. . .	. . .	. . .	. . .	0.20-0.40Ti 0.20-0.15Mg
C19280	bal(t)	0.50-1.5	0.30-0.7	0.30-0.7	. . .	. . .	0.005-0.015	. . .
C19400	97.0 min	2.1-2.6	. . .	0.05-0.20	. . .	0.03	0.015-0.15	. . .
C19410	bal(t)	1.8-2.3	0.6-0.9	0.10-0.20	. . .	. . .	0.015-0.050	. . .
C19450	bal(t)	1.5-3.0	0.8-2.5	. . .	. . .	. . .	0.005-0.05	. . .
C19500	96.0 min(t)	1.0-2.0	0.10-1.0	0.20-0.02	0.02	0.02	0.01-0.35	0.30-1.3Co
C19520	96.6 min(t)	0.50-1.5	. . .	. . .	. . .	0.01-3.5	. . .	
C19700	bal(t)	0.30-1.2	0.20	0.20	. . .	0.05	0.10-0.40	0.01-0.20Mg 0.05Ni 0.05Co 0.05Mn
C19750	bal(t)	0.35-1.2	0.05-0.40	0.20	. . .	0.05	0.10-0.40	0.01-0.20Mg 0.05Ni 0.05Co 0.05Mn
C19900	bal(p)	. . .	. . .	. . .	. . .	. . .	. . .	2.9-3.4Ti

Copper-zinc alloys (brasses)

Copper alloy No.	**Previous tradename**	**Composition, wt%**

alloy No.		**Cu**	**Pb**	**Fe**	**Zn**	**Other named elements**
C21000	Gilding, 95%	94.0-96.0(t)	0.03	0.05	bal	. . .
C22000	Commercial bronze, 90%	89.0-91.0(t)	0.05	0.05	bal	. . .
C22600	Jewelry bronze, 87 $\frac{1}{2}$ %	86.0-89.0(t)	0.05	0.05	bal	. . .
C23000	Red brass, 85%	84.0-86.0(t)	0.05	0.05	bal	. . .
C23030	. . .	83.5-85.5(t)	0.05	0.05	bal	0.20-0.40Si
C23400	. . .	81.0-84.0(t)	0.05	0.05	bal	. . .
C24000	Low brass, 80%	78.5-81.5(t)	0.05	0.05	bal	. . .
C24080	. . .	78.0-82.0(t)	0.20	. . .	bal	0.10Al
C26000	Cartridge brass, 70%	68.5-71.5(u)	0.07	0.05	bal	. . .
C26130	. . .	68.5-71.5(u)	0.05	0.05	bal	0.02-0.08As
C26200	. . .	67.0-70.0(u)	0.07	0.05	bal	. . .
C26800	Yellow brass, 66%	64.0-68.5(u)	0.15	0.05	bal	. . .
C27000	Yellow brass, 65%	63.0-68.5(u)	0.10	0.07	bal	. . .
C27200	. . .	62.0-65.0(u)	0.07	0.07	bal	. . .
C27400	Yellow brass, 63%	61.0-64.0(u)	0.10	0.05	bal	. . .
C28000	Muntz metal, 60%	59.0-63.0(u)	0.30	0.07	bal	. . .

Copper-zinc-lead alloys (leaded brasses)

Copper alloy No.	**Previous tradename**	**Composition, wt%**				
		Cu	**Pb**	**Fe**	**Zn**	**Other named elements**

C31200	. . .	87.5-90.5(v)	0.7-1.2	0.10	bal	0.25Ni
C31400	Leaded commercial bronze	87.5-90.5(v)	1.3-2.5	0.10	bal	0.7Ni
C31600	Leaded commercial bronze (nickel-bearing)	87.5-90.5(v)	1.3-2.5	0.10	bal	0.7-1.2Ni, 0.04-0.10P
C32000	Leaded red brass	83.5-86.5(v)	1.5-2.2	0.10	bal	0.25Ni
C33000	Low leaded brass (tube)	65.0-68.0(v)	0.25-0.7(w)	0.07	bal	. . .
C33200	High leaded brass (tube)	65.0-68.0(v)	1.5-2.5	0.07	bal	. . .
C33500	Low leaded brass	62.0-65.0(v)	0.25-0.7	0.15(x)	bal	. . .
C34000	Medium leaded brass, 64 $\frac{1}{2}$%	62.0-65.0(v)	0.8-1.5	0.15(x)	bal	. . .
C34200	High leaded brass, 64 $\frac{1}{2}$%	62.0-65.0(v)	1.5-2.5	0.15(x)	bal	. . .
C34500	. . .	62.0-65.0(v)	1.5-2.5	0.15	bal	. . .
C35000	Medium leaded brass, 62%	60.0-63.0(v)(y)	0.8-2.0	0.15(x)	bal	. . .
C35300	High leaded brass, 62%	60.0-63.0(p)(y)	1.5-2.5	0.15(x)	bal	. . .
C35330	. . .	60.5-64.0(p)	1.5-3.5(z)	. . .	bal	0.02-0.25As
C35600	Extra high leaded brass	60.0-63.0(p)	2.0-3.0	0.15(x)	bal	. . .
C36000	Free-cutting brass	60.0-63.0(p)	2.5-3.7	0.35	bal	. . .
C36500	Leaded Muntz metal uninhibited	58.0-61.0(v)	0.25-0.7	0.15	bal	0.25Sn
C37000	Free-cutting Muntz metal	59.0-62.0(v)	0.8-1.5	0.15	bal	. . .
C37100	. . .	58.0-62.0(v)	0.6-1.2	0.15	bal	. . .
C37700	Forging brass	58.0-61.0(p)	1.5-2.5	0.30	bal	. . .
C37710	. . .	56.5-60.0(p)	1.0-3.0	0.30	bal	. . .

C38000	Architectural bronze, low leaded	55.0-60.0(p)	1.5-2.5	0.35	bal	0.50Al 0.30Sn
C38500	Architectural bronze	55.0-59.0(p)	2.5-3.5	0.35	bal	. . .

Copper-zinc-tin alloys (tin brasses)

Copper alloy No.	**Previous tradename**	**Composition, wt%**						
		Cu	**Pb**	**Fe**	**Sn**	**Zn**	**P**	**Other named elements**
C40400	. . .	bal(u)	. . .	. . .	0.35-0.7	2.0-3.0	. . .	. . .
C40500	. . .	94.0-96.0(u)	0.05	0.05	0.7-1.3	bal	. . .	. . .
C41000	. . .	91.0-93.0(u)	0.05	0.05	2.0-2.8	bal	. . .	. . .
C41100	. . .	89.0-92.0(u)	0.10	0.05	0.30-0.7	bal	. . .	. . .
C41300	. . .	89.0-93.0(u)	0.10	0.05	0.7-1.3	bal	. . .	. . .
C41500	. . .	89.0-93.0(u)	0.10	0.05	1.5-2.2	bal	. . .	. . .
C42000	. . .	88.0-91.0(u)	. . .	. . .	1.5-2.0	bal	0.25	. . .
C42200	. . .	86.0-89.0(u)	0.05	0.05	0.8-1.4	bal	0.35	. . .
C42500	. . .	87.0-90.0(u)	0.05	0.05	1.5-3.0	bal	0.35	. . .
C43000	. . .	84.0-87.0(u)	0.10	0.05	1.7-2.7	bal	. . .	. . .
C43400	. . .	84.0-87.0(u)	0.05	0.05	0.40-1.0	bal	. . .	. . .

C43500	. . .	79.0-83.0(u)	0.10	0.05	0.6-1.2	bal	. . .	. . .
C43600	. . .	80.0-83.0(u)	0.05	0.05	0.20-0.50	bal	. . .	. . .
C44300	Admiralty, arsenical	70.0-73.0(v)	0.07	0.06	0.8-1.2(aa)	bal	. . .	0.02-0.06As
C44400	Admiralty, antimonial	70.0-73.0(v)	0.07	0.06	0.8-1.2(aa)	bal	. . .	0.02-0.10Sb
C44500	Admiralty, phosphorized	70.0-73.0(v)	0.07	0.06	0.8-1.2(aa)	bal	0.02-0.10	. . .
C46200	Naval brass, 63 $\frac{1}{2}$ %	62.0-65.0(v)	0.20	0.10	0.50-1.0	bal	. . .	. . .
C46400	Naval brass, uninhibited	59.0-62.0(v)	0.20	0.10	0.50-1.0	bal	. . .	. . .
C46500	Naval brass, arsenical	59.0-62.0(v)	0.20	0.10	0.50-1.0	bal	. . .	0.02-0.06As
C47000	Naval brass welding and brazing rod	57.0-61.0(v)	0.05	. . .	0.25-1.0	bal	. . .	0.01Al
C47940	. . .	63.0-66.0(v)	1.0-2.0	0.10-1.0	1.2-2.0	bal	. . .	0.10-0.50Ni (including Co)
C48200	Naval brass, medium leaded	59.0-62.0(v)	0.40-1.0	0.10	0.50-1.0	bal	. . .	. . .
C48500	Naval brass, high leaded	59.0-62.0(v)	1.3-2.2	0.10	0.50-1.0	bal	. . .	. . .
C48600	. . .	59.0-62.0(v)	1.0-2.5	. . .	0.8-1.5	bal	. . .	0.02-0.25As

Copper-tin-phosphorus alloys (phosphor bronzes)

Copper alloy No.	**Previous tradename**	**Composition, wt%**						
		Cu(p)	**Pb**	**Fe**	**Sn**	**Zn**	**P**	**Other named elements**

C50100	. . .	bal	0.05	0.05	0.50-0.8	. . .	0.01-0.05	. . .
C50200	. . .	bal	0.05	0.10	1.0-1.5	. . .	0.04	. . .
C50500	Phosphor bronze, 1.25% E	bal	0.05	0.10	1.0-1.7	0.30	0.03-0.35	. . .
C50700	. . .	bal	0.05	0.10	1.5-2.0	. . .	0.30	. . .
C50710	. . .	bal	. . .	. . .	1.7-2.3	. . .	0.15	0.10-0.40Ni
C50715	. . .	bal(bb)	0.02	0.05-0.15	1.7-2.3	. . .	0.025-0.04	. . .
C50900	. . .	bal	0.05	0.10	2.5-3.8	0.30	0.03-0.30	. . .
C51000	Phosphor bronze, 5% A	bal	0.05	0.10	4.2-5.8	0.30	0.03-0.35	. . .
C51100	. . .	bal	0.05	0.10	3.5-4.9	0.30	0.03-0.35	. . .
C51800	Phosphor bronze	bal	0.02	. . .	4.0-6.0	. . .	0.10-0.35	0.01Al
C51900	. . .	bal	0.05	0.10	5.0-7.0	0.30	0.03-0.35	. . .
C52100	Phosphor bronze, 8% C	bal	0.05	0.10	7.0-9.0	0.20	0.03-0.35	. . .
C52400	Phosphor bronze, 10% D	bal	0.05	0.10	9.0-11.0	0.20	0.03-0.35	

Copper-tin-lead phosphorus alloys (leaded phosphor bronzes)							
Copper alloy No.	**Previous tradename**	**Composition, wt%**					
		Cu(p)	**Pb**	**Fe**	**Sn**	**Zn**	**P**
C53400	Phosphor bronze B-1	bal	0.8-1.2	0.10	3.5-5.8	0.30	0.03-0.35
C54400	Phosphor bronze B-2	bal	3.5-4.5	0.10	3.5-4.5	1.5-4.5	0.01-0.50

Copper-phosphorus and copper-silver-phosphorus alloys (brazing alloys)			
Copper alloy No.	**Composition, wt%**		
	Cu(cc)	**Ag**	**P**

C55180	bal	. . .	4.8-5.2
C55181	bal	. . .	7.0-7.5
C55280	bal	1.8-2.2	6.8-7.2
C55281	bal	4.8-5.2	5.8-6.2
C55282	bal	4.8-5.2	6.5-7.0
C55283	bal	5.8-6.2	7.0-7.5
C55284	bal	14.5-15.5	4.8-5.2

Copper-aluminum alloys (aluminum bronzes)

Copper alloy No.	**Composition, wt%**									
	Cu(p) (including Ag)	**Pb**	**Fe**	**Sn**	**Zn**	**Al**	**Mn**	**Si**	**Ni (including Co)**	**Other named elements**
C60800	bal	0.10	0.10	. . .	. . .	5.0-6.5	. . .	. . .	. . .	0.02-0.35As
C61000	bal	0.02	0.50	. . .	0.20	6.0-8.5	. . .	0.10	. . .	. . .
C61300	bal(t)	0.01	2.0-3.0	0.20-0.50	0.10(dd)	6.0-7.5	0.20	0.10	0.15	0.015P(dd)
C61400	bal	0.01	1.5-3.5	. . .	0.20	6.0-8.0	1.0	. . .	. . .	0.015P
C61500	bal	0.015	. . .	. . .	. . .	7.7-8.3	. . .	. . .	1.8-2.2	. . .
C61550	bal	0.05	0.20	0.05	0.8	5.5-6.5	1.0	. . .	1.5-2.5	0.8Zn
C61800	bal	0.02	0.50-1.5	. . .	0.02	8.5-11.0	. . .	0.10	. . .	. . .
C61900	bal	0.02	3.0-4.5	0.6	0.8	85-10.0	. . .	. . .	. . .	. . .
C62200	bal	0.02	3.0-4.2	. . .	0.02	11.0-12.0	. . .	0.10	. . .	. . .

C62300	bal	. . .	2.0-4.0	0.6	. . .	8.5-10.0	0.50	0.25	1.0	. . .
C62400	bal	. . .	2.0-4.5	0.20	. . .	10.0-11.5	0.30	0.25	. . .	. . .
C62500	bal	. . .	3.5-5.5	. . .	. . .	12.5-13.5	2.0	. . .	. . .	. . .
C62580	bal	0.02	3.0-5.0	. . .	0.02	12.0-13.0	. . .	0.04	. . .	. . .
C62581	bal	0.02	3.0-5.0	. . .	0.02	13.0-14.0	. . .	0.04	. . .	. . .
C62582	bal	0.02	3.0-5.0	. . .	0.02	14.0-15.0	. . .	0.04	. . .	. . .
C63000	bal	. . .	2.0-4.0	0.20	0.30	9.0-11.0	1.5	0.25	4.0-5.5	. . .
C63010	78.0 min(t)	. . .	2.0-3.5	0.20	0.30	9.7-10.9	1.5	. . .	4.5-5.5	. . .
C63020	74.5 min	0.03	4.0-5.5	0.25	0.30	10.0-11.0	1.5	. . .	4.2-6.0	0.20Co 0.05cr
C63200	bal	0.02	3.5-4.3(ee)	. . .	. . .	8.7-9.5	1.2-2.0	0.10	4.0-4.8(ee)	. . .
C63280	bal	0.02	3.0-5.0	. . .	. . .	8.5-9.5	0.6-3.5	. . .	4.0-5.5	. . .
C63380	bal	0.02	2.0-4.0	. . .	0.15	7.0-8.5	11.0-14.0	0.10	1.5-3.0	. . .
C63400	bal	0.05	0.15	0.20	0.50	2.6-3.2	. . .	0.25-0.45	0.15	0.15As
C63600	bal	0.05	0.15	0.20	0.50	3.0-4.0	. . .	0.7-1.3	0.15	0.15As
C63800	bal	0.05	0.20	. . .	0.8	2.5-3.1	0.10	1.5-2.1	0.20(ff)	0.25-0.55Co
C64200	bal	0.05	0.30	0.20	0.50	6.3-7.6	0.10	1.5-2.2	0.25	0.15As
C64210	bal	0.05	0.30	0.20	0.50	6.3-7.0	0.10	1.5-2.0	0.25	0.15As
Copper-silicon alloys (silicon bronzes)										

Copper alloy No.	**Previous tradename**	**Composition, wt%**								
		Cu(p) (including Ag)	**Pb**	**Fe**	**Sn**	**Zn**	**Mn**	**Si**	**Ni (including Co)**	**Other named elements**
C64700	. . .	bal	0.10	0.10	. . .	0.50	. . .	0.40-0.8	1.6-2.2	. . .
C64710	. . .	95.0 min	. . .	. . .	. . .	0.20-0.50	0.10	0.50-0.9	2.9-3.5	. . .
C64730	. . .	93.5 min	. . .	. . .	1.0-1.5	0.20-0.50	0.10	0.50-0.9	2.9-3.5	. . .
C64900	. . .	bal	0.05	0.10	1.2-1.6	0.20	. . .	0.8-1.2	0.10	0.10Al
C65100	Low silicon bronze B	bal	0.05	0.8	. . .	1.5	0.7	0.8-2.0	. . .	. . .
C65400	. . .	bal	0.05	. . .	1.2-1.9	0.50	. . .	2.7-3.4	. . .	0.01-0.12Cr
C65500	High silicon bronze A	bal	0.05	0.8	. . .	1.5	0.50-1.3	2.8-3.8	0.6	. . .
C65600	. . .	bal	0.02	0.50	1.5	1.5	1.5	2.8-4.0	. . .	0.01Al
C66100	. . .	bal	0.20-0.8	0.25	. . .	1.5	1.5	2.8-3.5	. . .	. . .

Other copper-zinc alloys

Copper alloy No.	**Previous tradename**	**Composition, wt%**								
		Cu(p) (including Ag)	**Pb**	**Fe**	**Sn**	**Zn**	**Ni (including Co)**	**Al**	**Mn**	**Si**	**Other named elements**
C66400	. . .	bal	0.015	1.3-1.7(gg)	0.05	11.0-12.0	. . .	. . .	. . .	. . .	0.30-0.7Co(gg)
C66410	. . .	bal	0.015	1.8-2.3	0.05	11.0-12.0	. . .	. . .	. . .	. . .	. . .

C66700	Manganese brass	68.5-71.5	0.07	0.10	. . .	bal	. . .	. . .	0.8-1.5	. . .	. . .
C66800	. . .	60.0-63.0	0.50	0.35	0.30	bal	0.25	0.25	2.0-3.5	0.50-1.5	. . .
C67000	Manganese bronze B	63.0-68.0	0.20	2.0-4.0	0.50	bal	. . .	3.0-6.0	2.5-5.0	. . .	. . .
C67300	. . .	58.0-63.0	0.40-3.0	0.50	0.30	bal	0.25	0.25	2.0-3.5	0.50-1.5	. . .
C67400	. . .	57.0-60.0	0.50	0.35	0.30	bal	0.25	0.50-2.0	2.0-3.5	0.50-1.5	. . .
C67500	Manganese bronze A	57.0-60.0	0.20	0.8-2.0	0.50-1.5	bal	. . .	0.25	0.05-0.50	. . .	. . .
C67600	. . .	57.0-60.0	0.50-1.0	0.40-1.3	0.50-1.5	bal	. . .	. . .	0.05-0.50	. . .	. . .
C68000	Bronze, low fuming (nickel)	56.0-60.0	0.05	0.25-1.25	0.75-1.10	bal	0.20-0.8	0.01	0.01-0.50	0.04-0.15	. . .
C68100	Bronze, low fuming	56.0-60.0	0.05	0.25-1.25	0.75-1.10	bal	. . .	0.01	0.01-0.50	0.04-0.15	. . .
C68700	Aluminum brass, arsenical	76.0-79.0	0.07	0.06	. . .	bal	. . .	1.8-2.5	. . .	. . .	0.02-0.06As
C68800	. . .	bal	0.05	0.20	. . .	21.3-24.1(hh)	. . .	3.0-3.8(hh)	. . .	. . .	0.25-0.55Co
C69050	. . .	70.0-75.0	. . .	. . .	. . .	bal	0.50-1.5	3.0-4.0	. . .	0.10-0.6	0.01-0.20Zr
C69100	. . .	81.0-84.0	0.05	0.25	0.10	bal	0.8-1.4	0.7-1.2	0.10min	0.8-1.3	. . .
C69400	Silicon red brass	80.0-83.0	0.30	0.20	. . .	bal	. . .	. . .	. . .	3.5-4.5	. . .
C69430	. . .	80.0-83.0	0.30	0.20	. . .	bal	. . .	. . .	. . .	3.5-4.5	0.03-0.06As
C69700	. . .	75.0-80.0	0.50-	0.20	. . .	bal	. . .	. . .	0.40	2.5-	. . .

			1.5						3.5	
C69710	. . .	75.0-80.0	0.50-1.5	0.20	. . .	bal	. . .	. . .	0.40	2.5-3.5	0.03-0.06As

Copper-nickel alloys

Copper alloy No.	**Previous tradename**	**Composition, wt%**							
		Cu (including Ag)	**Pb**	**Fe**	**Zn**	**Ni (including Co)**	**Sn**	**Mn**	**Other named elements**
C70100	. . .	bal(p)	. . .	0.05	0.25	3.0-4.0	. . .	0.50	. . .
C70200	. . .	bal(p)	0.05	0.10	. . .	2.0-3.0	. . .	0.40	. . .
C70250	. . .	bal(p)	0.05	0.20	1.0	2.2-4.2	. . .	0.10	0.05-0.30Mg 0.25-1.2Si
C70400	Copper-nickel, 5%	rem(p)	0.05	1.3-1.7	1.0	4.8-6.2	. . .	0.30-0.8	. . .
C70500	Copper-nickel, 7%	bal(p)	0.05	0.10	0.20	5.8-7.8	. . .	0.15	. . .
C70600	Copper-nickel, 10%	bal(p)	0.05(ii)	1.0-1.8	1.0(ii)	9.0-11.0	. . .	1.0	(ii)
C70610	. . .	bal(p)	0.01	1.0-2.0	. . .	10.0-11.0	. . .	0.50-1.0	0.05S 0.05C
C70690	. . .	bal(p)	0.001	0.005	0.001	9.0-11.0	. . .	0.001	(jj)
C70700	. . .	bal(p)	. . .	0.05	. . .	9.5-10.5	. . .	0.50	. . .
C70800	Copper-nickel, 11%	bal(p)	0.05	0.10	0.20	10.5-12.5	. . .	0.15	. . .
C71000	Copper-nickel, 20%	bal(p)	0.05	1.0	1.0	19.0-23.0	. . .	1.0	. . .
C71100	. . .	bal(p)	0.05	0.10	0.20	22.0-24.0	. . .	0.15	. . .
C71300	. . .	bal(p)	0.05	0.20	1.0	23.5-26.5	. . .	1.0	. . .
C71500	Copper-nickel, 30%	bal(p)	0.05(ii)	0.40-1.0	1.0(ii)	29.0-33.0	. . .	1.0	(ii)

C71580	. . .	bal(p)	0.05	0.50	0.05	29.0-33.0	. . .	0.30	(kk)
C71581	. . .	bal(p)	0.02	0.40-0.7	. . .	29.0-32.0	. . .	1.0	(ll)
C71590	. . .	bal	0.001	0.15	0.001	29.0-31.0	0.001	0.50	(jj)
C71640	. . .	bal(p)	0.01	1.7-2.3	. . .	29.0-32.0	. . .	1.5-2.5	0.03S 0.06C
C71700	. . .	bal(p)	. . .	0.40-1.0	. . .	29.0-33.0	. . .	. . .	0.30-0.7Be
C71900	. . .	bal(p)	0.015	0.50	0.05	28.0-33.0	. . .	0.20-1.0	2.2-3.0Cr 0.02-0.35Zr 0.01-0.20Ti 0.04C 0.25Si 0.15S 0.02P
C72150	. . .	bal(p)	0.05	0.10	0.20	43.0-46.0	. . .	0.05	0.10C 0.50Si
C72200	. . .	bal(t)	0.05(ii)	0.50-1.0	1.0(ii)	15.0-18.0	. . .	1.0	0.30-0.7Cr 0.03Si 0.03Ti (ii)
C72420	. . .	bal(u)	0.02	0.7-1.2	0.20	13.5-16.5	0.10	3.5-5.5	1.0-2.0Al 0.50Cr 0.15Si 0.05Mg 0.15S 0.01P 0.05C
C72500	. . .	bal(t)	0.05	0.6	0.50	8.5-10.5	1.8-2.8	0.20	. . .
C72650	. . .	bal(u)	0.01	0.10	0.10	7.0-8.0	45-5.5	0.10	. . .
C72700	. . .	bal(u)	0.02	0.50	0.50	8.5-9.5	5.5-6.5	0.5-0.30	0.10Nb 0.15Mg
C72800	. . .	bal(u)	0.005	0.50	1.0	9.5-10.5	7.5-8.5	0.05-0.30	0.10Al 0.001B 0.001Bi 0.10-0.30Nb 0.005-0.15Mg 0.005P 0.0025S

									0.02Sb 0.05Si 0.01Ti
C72900	. . .	bal(u)	0.02(mm)	0.50	0.50	14.5-15.5	7.5-8.5	0.30	0.10Nb 0.15Mg
C72950	. . .	bal(u)	0.05	0.6	. . .	20.0-22.0	4.5-5.7	0.6	. . .

Copper-nickel-zinc alloys (nickel silvers)

Copper alloy No.	**Previous tradename**	**Composition, wt%**						
		Cu(p) (including Ag)	**Pb**	**Fe**	**Zn**	**Ni (including Co)**	**Mn**	**Other named elements**
C73500	. . .	70.5-73.5	0.10	0.25	bal	16.5-19.5	0.50	. . .
C74000	. . .	69.0-73.5	0.10	0.25	bal	9.0-11.0	0.50	. . .
C74300	. . .	63.0-66.0	0.10	0.25	bal	7.0-9.0	0.50	. . .
C74500	Nickel silver, 65-10	63.5-66.5	0.10(nn)	0.25	bal	9.0-11.0	0.50	. . .
C75200	Nickel silver, 65-18	63.5-66.5	0.05	0.25	bal	165-19.5	0.50	. . .
C75400	Nickel silver, 65-15	63.5-66.5	0.10	0.25	bal	14.0-16.0	0.50	. . .
C75700	Nickel silver, 65-12	63.5-66.5	0.05	0.25	bal	11.0-13.0	0.50	. . .
C76000	. . .	60.0-63.0	0.10	0.25	bal	16.5-19.5	0.50	. . .
C76200	. . .	57.0-61.0	0.10	0.25	bal	11.0-13.5	0.50	. . .
C76400	. . .	58.5-61.5	0.05	0.25	bal	16.5-19.5	0.50	. . .
C76700	Nickel silver, 56.5-15	55.0-58.0	. . .	. . .	bal	14.0-16.0	0.50	. . .
C77000	Nickel silver, 55-18	53.5-56.5	0.05	0.25	bal	16.5-19.5	0.50	. . .
C77300	. . .	46.0-50.0	0.05	. . .	bal	9.0-11.0	. . .	0.01Al 0.25P 0.04-0.25Si

C77400	. . .	43.0-47.0	0.20	. . .	bal	9.0-11.0	. . .	. . .
C78200	. . .	63.0-67.0	1.5-2.5	0.35	bal	7.0-9.0	0.50	. . .
C79000	. . .	63.0-67.0	1.5-2.2	0.35	bal	11.0-13.0	0.50	. . .
C79200	. . .	59.0-66.5	0.8-1.4	0.25	bal	11.0-13.0	0.50	. . .
C79800	. . .	45.5-48.5	1.5-2.5	0.25	bal	9.0-11.0	1.5-2.5	. . .

Source: Copper Development Association Inc.

(a) These are high conductivity coppers, which have in the annealed condition a minimum conductivity of 100%IACS.

(b) Copper is determined by the difference between the impurity total and 100%.

(c) The following additional maximum limits apply: Bi, 1 ppm(0.0001%); Cd, 1 ppm (0.001%); Fe, 10 ppm (0.0010%); Pb, 5 ppm (0.0005%);Mn, 0.5 ppm (0.00005%); Hg, 1 ppm (0.0001%); Ni, 10 ppm (0.0010%); oxygen, 5 ppm (0.0005%); Se, 3 ppm (0.0003%); Ag, 25 ppm (0.0025%); S, 15 ppm (0.0015%);Sn, 2 ppm (0.0002%); Zn, 1 ppm (0.0001%).

(d) Includes P.

(e) The following additional maximum limits apply: Oxygen and trace elements can vary depending on the process.

(f) Se, 2 ppm (0.0002%);Bi, 1.0 ppm (0.00010%); group total, Te + Se + Bi, 3 ppm (0.0003%). Sn, 5 ppm (0.0005%); Pb, 5 ppm (0.0005%); Fe, 10 ppm (0.0010%); Ni, 10 ppm (0.0010%);S, 15 ppm (0.0015%); Ag, 25 ppm (0.0025%); oxygen, 100-650 ppm (0.010-.065%). The total maximum allowable of 65 ppm (0.0065%) does not include oxygen.

(g) Small amounts of Cd or other elements can be added by agreement to improve the resistance to softening at elevated temperatures.

(h) Includes B +P.

(i) This includes oxygen-free copper, which contains P in an agreed-upon amount.

(j) Includes Te + Se.

(k) Includes Cd. Deoxidized with lithium or other suitable agreed-upon elements.

(l) Includes Cu + Ag + Sn.

(m) Includes Te.

(n) Includes oxygen-free or deoxidized grades with deoxidizers(such as phosphorus, boron, lithium, or other) in an agreed-upon amount.

(o) All aluminum present as Al_2O_3; 0.04% oxygen present as Cu_2O with a negligible amount in solid solution with copper.

(p) Cu + sum of named elements, 99.5% min.

(q) Ni + Co, 0.20% min; Ni + Fe + Co, 0.6% max.

(r) Includes Co.

(s) Cu + sum of named elements, 99.9% min.

(t) Cu + sum of named elements, 99.8% min.

(u) Cu + sum of named elements, 99.7% min.

(v) Cu + sum of named elements, 99.6% min.

(w) For tube over 5 in. outside diameter, the Pb can be <0.20%.

(x) For flat products, the iron is 0.10%max.

(y) Cu, 61.0% min for rod.

(z) Pb can be reduced to 1.0%by agreement.

(aa) For tubular products, the minimum Sn content can be 0.9%.

(bb) Cu + Sn + Fe + P, 99.5% min.

(cc) Cu + sum of named elements, 99.85% min.

(dd) When the product is for subsequent welding applications and is so specified by the purchaser, Cr, Cd, Zr, and Zn will each be 0.05% max.

(ee) Fe content shall not exceed Ni content.

(ff) Not including Co.

(gg) Fe + Co, 1.8-2.3%.

(hh) Al + Zn, 25.1-27.1%.

(ii) The following additional maximum limits apply: When the product is for subsequent welding applications and is so specified by the purchaser, 0.50% Zn, 0.02% P, 0.02% Pb, 0.02% S (0.008% S for C71110), and 0.05% C.

(jj) The following additional maximum limits apply: 0.02% C, 0.015% Si, 0.003% S, 0.002% Al, 0.001% P, 0.0005%Hg, 0.001% Ti, 0.001% Sb, 0.001% As, 0.001% Bi, 0.05% Co, 0.10% Mg, and 0.005%oxygen. For C70690, Co will be 0.02% max.

(kk) The following maximum limits apply: 0.07% C, 0.15% Si, 0.024% S, 0.05%Al, and 0.03% P.

(ll) 0.02% P, max;0.25% Si, max; 0.01% S, max; 0.20-0.50% Ti.

(mm) 0.005% Pb, max, for hot rolling.

(nn) 0.05% Pb, max, for rod and wire.

Table 7 Properties of wrought copper and copper alloys

Alloy No.	Commercial forms[a]	Mechanical properties[b]				Elongation in 50 mm (2 in.)[b], %	Machinability rating[c], %
		Tensile strength		**Yield strength**			
		MPa	**ksi**	**MPa**	**ksi**		
C10100	F, R, W, T, P, S	221-455	32-66	69-365	10-53	55-4	20
C10200	F, R, W, T, P, S	221-455	32-66	69-365	10-53	55-4	20
C10300	F, R, T, P, S	221-379	32-55	69-345	10-50	50-6	20
C10400, C10500, C10700	F, R, W, S	221-455	32-66	69-365	10-53	55-4	20
C10800	F, R, T, P	221-379	32-55	69-345	10-50	50-4	20
C11000	F, R, W, T, P, S	221-455	32-66	69-365	10-53	55-4	20

C11100	W	455	66	. . .	. . .	1.5 in 1500 mm (60 in.)	20
C11300, C11400, C11500, C11600	F, R, W, T, S	221-455	32-66	69-365	10-53	55-4	20
C12000, C12100	F, T, P	221-393	32-57	69-365	10-53	55-4	20
C12200, C12210	F, R, T, P, S	221-379	32-55	69-345	10-50	45-8	20
C12500, C12700, C12800, C12900, C13000	F, R, W, S	221-462	32-67	69-365	10-53	55-4	20
C14200	F, R, T	221-379	32-55	69-345	10-50	45-8	20
C14300	F	221-400	32-58	76-386	11-56	42-1	20
C14310	F	221-400	32-58	76-386	11-56	42-1	20
C14500, C14510, C14520	F, R, W, T, S	221-386	32-56	69-352	10-51	50-3	85
C14700, C14710, C14720	F, R, W, S	221-393	32-57	69-379	10-55	52-8	85
C15000	R, W	200-524	29-76	41-496	6-72	54-1.5	20
C15100	F	262-469	38-68	69-455	10-66	36-2	20
C15500	F	276-552	40-80	124-496	18-72	40-3	20
C15710	R, W	324-724	47-105	268-689	39-100	20-10	. . .
C15715	F, R, S	358-607	52-88	283-579	41-84	27-1	20
C15720	F, R	462-614	67-89	365-586	53-85	20-3.5	. . .

C15735	R	483-586	70-85	414-565	60-82	16-10	. . .
C15760	F, R	483-648	70-94	386-552	56-80	20-8	. . .
C16200, C16210	F, R, W	241-689	35-100	48-476	7-69	57-1	20
C16500	F, R, W	276-655	40-95	97-490	14-71	53-1.5	20
C17000	F, R	483-1310	70-190	221-1172	32-170	45-3	20
C17200	F, R, W, T, P, S	469-1462	68-212	172-1344	25-195	48-1	20
C17300	R	469-1479	68-200	172-1255	25-182	48-3	50
C17400	F	620-793	90-115	172-758	25-110	12-4	20
C17410	F, R	758-896	110-130	655-758	95-110	12-4	. . .
C17500, C17510	F, R, S, T	310-793	45-115	172-758	25-110	28-5	. . .
C18090	F	414-690	60-100	345-600	50-87	25-9	20
C18100	R, W	483-586	70-85	434-517	63-75	13-4	. . .
C18135	F, R, W	221-483	32-70	69-434	10-63	55-10	20
C18200, C18400, C18500	F, W, R, S, T	234-593	34-86	97-531	14-77	40-5	20
C18700	R	221-379	32-55	69-345	10-50	45-8	85
C18900	R, W	262-655	38-95	62-359	9-52	48-14	20

C19000	F, R, W	262-793	38-115	138-552	20-80	50-2	30
C19100	R, F	248-717	36-104	69-634	10-92	27-6	75
C19200	F, T	255-531	37-77	76-510	11-74	40-2	20
C19210	F	296-538	43-78	152-531	22-77	38-1.5	20
C19220	F	310-524	45-76	. . .	. . .	30-5	. . .
C19280	F	538-572	78-83	. . .	. . .	12-3	. . .
C19400	F	310-524	45-76	165-503	24-73	32-2	20
C19500	F	552-669	80-97	448-655	65-95	15-2	20
C19700	F	344-517	50-75	165-503	24-73	32-2	20
C21000	F, W	234-441	34-64	69-400	10-58	45-4	20
C22000	F, R, W, T	255-496	37-72	69-427	10-62	50-3	20
C22600	F, W	269-669	39-97	76-427	11-62	46-3	30
C23000	F, W, T, P	269-724	39-105	69-434	10-63	55-3	30
C24000	F, W	290-862	42-125	83-448	12-65	55-3	30
C26000, C26100, C26130, C26200	F, R, W, T, S	303-896	44-130	76-448	11-65	66-3	30
C26800, C27000	F, R, W	317-883	46-128	97-427	14-62	65-3	30

C27400	T, W	386-510	56-74	159-379	23-55	50-10	35
C28000	F, R, T	372-510	54-74	145-379	21-55	52-10	40
C31400	F, R	255-414	37-60	83-379	12-55	45-10	80
C31600	F, R	255-462	37-67	83-407	12-59	45-12	80
C32000	R, S	276-496	40-72	110-414	16-60	45-4	90
C33000	T	324-517	47-75	103-414	15-60	60-7	60
C33200	T	359-517	52-75	138-414	20-60	50-7	80
C33500	F	317-510	46-74	97-414	14-60	65-8	60
C34000	F, R, W, S	324-607	47-88	103-414	15-60	60-7	70
C34200	F, R	338-586	49-85	117-427	17-62	52-5	90
C34900	R, W	365-469	53-68	110-379	16-55	72-18	50
C35000	F, R	310-655	45-95	90-483	13-70	66-1	70
C35300	F, R	338-586	49-85	117-427	17-62	52-5	90
C35600	F	338-510	49-74	117-414	17-60	50-7	100
C36000	F, R, S	338-469	49-68	124-310	18-45	53-18	100
C36500 to C36800[(d)]	F	372	54	138	20	45	60

C37000, C37100	T	372-552	54-80	138-414	20-60	40-6	70
C37700(e)	R, S	359	52	138	20	45	80
C38500(e)	R, S	414	60	138	20	30	90
C40500	F	269-538	39-78	83-483	12-70	49-3	20
C40800	F	290-545	42-79	90-517	13-75	43-3	20
C41100	F, W	269-731	39-106	76-496	11-72	13-2	20
C41300	F, R, W	283-724	41-105	83-565	12-82	45-2	20
C41500	F	317-558	46-81	117-517	17-75	44-2	30
C42200	F	296-607	43-88	103-517	15-75	46-2	30
C42500	F	310-634	45-92	124-524	18-76	49-2	30
C43000	F	317-648	46-94	124-503	18-73	55-3	30
C43400	F	310-607	45-88	103-517	15-75	49-3	30
C43500	F, T	317-552	46-80	110-469	16-68	46-7	30
C44300, C44400, C44500	F, W, T	331-379	48-55	124-152	18-22	65-60	30
C46400 to C46700	F, R, T, S	379-607	55-88	172-455	25-66	50-17	30
C48200	F, R, S	386-517	56-75	172-365	25-53	43-15	50

C48500	F, R, S	379-531	55-77	172-365	25-53	40-15	70
C50500	F, W	276-545	40-79	97-345	14-50	48-4	20
C51000	F, R, W, T	324-965	47-140	131-552	19-80	64-2	20
C51100	F	317-710	46-103	345-552	50-80	48-2	20
C52100	F, R, W	379-965	55-140	165-552	24-80	70-2	20
C52400	F, R, W	455-1014	66-147	193 (Annealed)	28 (Annealed)	70-3	20
C54400	F, R	303-517	44-75	131-434	19-63	50-16	80
C60800	T	414	60	186	27	55	20
C61000	R, W	483-552	70-80	207-379	30-55	65-25	20
C61300	F, R, T, P, S	483-586	70-85	207-400	30-58	42-35	30
C61400	F, R, W, T, P, S	524-614	76-89	228-414	33-60	45-32	20
C61500	F	483-1000	70-145	152-965	22-140	55-1	30
C61800	R	552-586	80-85	269-293	39-42.5	28-23	40
C61900	F	634-1048	92-152	338-1000	49-145	30-1	. . .
C62300	F, R	517-676	75-98	241-359	35-52	35-22	50
C62400	F, R	621-724	90-105	276-359	40-52	18-14	50

C62500(e)	F, R	689	100	379	55	1	20
C63000	F, R	621-814	90-118	345-517	50-75	20-15	30
C63200	F, R	621-724	90-105	310-365	45-53	25-20	30
C63600	R, W	414-579	60-84	. . .	. . .	64-29	40
C63800	F	565-896	82-130	372-786	54-114	36-4	. . .
C64200	F, R	517-703	75-102	241-469	35-68	32-22	60
C64400	F	483-952	70-138	345-903	50-131	37-3	. . .
C65100	R, W, T	276-655	40-95	103-476	15-69	55-11	30
C65400	F	276-793	40-115	130-744	20-108	40-3	20
C65500	F, R, W, T	386-1000	56-145	145-483	21-70	63-3	30
C66700	F, W	315-689	45.8-100	83-638	12-92.5	60-2	30
C67400	F, R	483-634	70-92	234-379	34-55	28-20	25
C67500	R, S	448-579	65-84	207-414	30-60	33-19	30
C68700	T	414	60	186	27	55	30
C68800	F	565-889	82-129	379-786	55-114	36-2	. . .
C69000	F	496-896	72-130	345-807	50-117	40-2	. . .

C69400	R	552-689	80-100	276-393	40-57	25-20	30
C70250	F	586-758	85-110	552-784	80-105	40-3	20
C70400	F, T	262-531	38-77	276-524	40-76	46-2	20
C70600	F, T	303-414	44-60	110-393	16-57	42-10	20
C71000	F, W, T	338-655	49-95	90-586	13-85	40-3	20
C71300	F	338-655	49-95	90-586	13-85	40-3	20
C71500	F, R, T	372-517	54-75	138-483	20-70	45-15	20
C71700	F, R, W	483-1379	70-200	207-1241	30-180	40-4	20
C72200	F, T	317-483	46-70	124-455	18-66	46-6	. . .
C72500	F, R, W, T	379-827	55-120	152-745	22-108	35-1	20
C72600	F, R, W, T, P, S	565-793	82-115	496-683	72-99	12-1	. . .
C72700	F, W, T, P, S	455-1144	66-166	200-986	29-143	36-1.7	. . .
C72800	F, W, T, P, S	524-1372	76-199	434-1351	63-196	23-3.7	10
C72900	F, R, T, P, S	931-1379	135-200	758-1172	110-170	7-2.4	. . .
C73500	F, R, W, T	345-758	50-110	103-579	15-84	37-1	20
C74500	F, W	338-896	49-130	124-524	18-76	50-1	20

C75200	F, R, W	386-710	56-103	172-621	25-90	45-3	20
C75400	F	365-634	53-92	124-545	18-79	43-2	20
C75700	F, W	359-641	52-93	124-545	18-79	48-2	20
C76200	F, T	393-841	57-122	145-758	21-110	50-1	. . .
C76390	R	621	90	586	85	6	40
C77000	F, R, W	414-1000	60-145	186-621	27-90	40-2	30
C72200	F, T	317-483	46-70	124-455	18-66	46-6	. . .
C78200	F	365-627	53-91	159-524	23-76	40-3	60

Source: Copper Development Association Inc.

(a) F, flat products; R, rod; W, wire; T, tube; P, pipe; S, shapes.

(b) Ranges are from softest to hardest commercial forms. The strength of the standard copper alloys depends on the temper (annealed grain size or degree of cold work) and the section thickness of the mill product. Ranges cover standard tempers for each alloy.

(c) Based on 100% for C36000.

(d) Values are for as-hot-rolled material.

(e) Values are for as-extruded material.

Types

The pure copper alloys, also called the coppers (C10100 to C15900), are melted and cast in inert atmosphere from the highest-purity copper in order to maintain high-electrical conductivity(oxygen-free, or OF, copper, C10200). Copper is more commonly cast with a controlled oxygen content (0.04% O as in electrolytic tough pitch, or ETP, copper, C11000) to refine out impurity elements from solution by oxidation. Included in this group are the alloys that are deoxidized with small addition of various elements such as phosphorus (C12200, or Cu-0.03P) and the alloys that use minor amounts of alloy additions to greatly improve softening resistance, such as the silver-bearing copper alloys (C10500, Cu-0.034 min Ag) and the zirconium-bearing alloys (C15000 and C15100, Cu-0.1Zr).

High-copper alloys (C16000 to C19900) are designed to maintain high conductivity while using dispersions and precipitates to increase strength and soften resistance: iron dispersions in Cu-(1.0-2.5)Fe alloys (C19200, C19400), chromium precipitates in Cu-1Cr (C18200), and the coherent precipitates in the Cu-(0.3-2.0)Be-Co,Ni age-hardening alloys (C17200, C17410, and C17500).

Brass alloys are a rather large family of copper-zinc alloys. A significant number of these are binary copper-zinc alloys (C20500 to C28000), utilizing the extensive region of solid solution up to 35% Zn, offering excellent formability with good work-hardening strength at reasonable cost. (These alloys are commonly referred to as alpha brasses.)The alloys below 15% Zn have good corrosion and stress-corrosion resistance. Alloys above 15% Zn need a stress-relieving heat treatment to avoid stress corrosion and, under certain conditions, can be susceptible to dezincification. Alloys at the higher zinc levels of 35 to 40% Zn contain the body-centered cubic (bcc) beta phase, especially at elevated temperatures, making them hot extrudeable and forgeable (alloy C28000 with Cu-40Zn, for example). The beta alloys are also capable of being hot worked while containing additions of 1 to 4% Pb, or more recently bismuth, elements added to provide the dispersion of coarse particles that promote excellent machinability characteristics available with various commercial Cu-Zn-Pb alloys(C31200 to C38500). The tin brasses (C40400 to C49000) contain various tin additions from 0.3 to 3.0% to enhance corrosion resistance and strength in brass alloys. Besides improving corrosion-resistance properties in copper-zinc tube alloys, such as C44300 (Cu-30Zn-1Sn), the tin addition also provides for good combinations of strength, formability, and electrical conductivity required by various electrical connectors, such as C42500 (Cu-10Zn-2Sn). A set of miscellaneous copper-zinc alloys (C66400 to C69900) provide improved strength and corrosion resistance through solution hardening with aluminum, silicon, and manganese, as well as dispersion hardening with iron additions.

Bronze alloys consist of several families named for the principal solid-solution alloying element. The familiar tin bronzes (C50100 to C54400) comprise a set of good work-hardening, solid-solution alloys containing from nominally 0.8% Sn (C50100) to 10% Sn (C52400), usually with a small addition of phosphorus for deoxidation. These alloys provide an excellent combination of strength, formability, softening resistance, electrical conductivity, and corrosion resistance. The aluminum-bronze alloys contain 2 to 15% Al (C60800 to C64200), an element adding good-solid-solution strengthening and work hardening, as well as corrosion resistance. The aluminum-bronzes usually contain 1 to 5% Fe, providing elemental dispersions to promote dispersion strengthening and grain size control. The silicon-bronze alloys (C64700 to C66100) generally offer good strength through solution- and work-hardening characteristics, enhanced in some cases with a tin addition, as well as excellent resistance to stress corrosion and general corrosion.

Cupronickels are copper-nickel alloys (C70100 to C72900) that utilize the complete solid solubility that copper has for nickel to provide a range of single-phase alloys (C70600 with Cu-10Ni-1.5Fe, and C71500 with Cu-30Ni-0.8Fe, for example) that offer excellent corrosion resistance and strength. The family of copper-nickel alloys also includes various dispersion- and precipitation-hardening alloys due to the formation of hardening phases with third elements, such as Ni_2Si in C70250 (Cu-3Ni-0.7Si-0.15Mg) and the spinodal hardening obtainable in the Cu-Ni-Sn alloys (C72700 with Cu-10Ni-8Sn, for example).

Copper-nickel-zinc alloys, also called nickel-silvers, are a family of solid-solution-strengthening and work-hardening alloys with various nickel-zinc levels in the Cu-(4-26)Ni-(3-30)Zn ternary alloy system valued for their strength, formability, and corrosion and tarnish resistance, and for some applications, metallic white color.

Strengthening Mechanisms for Wrought Copper Alloys

Solution Hardening. Copper can be hardened by the various common methods without unduly impairing ductility or electrical conductivity. The metallurgy of copper alloys is suited for using, singly or in combination, the various common strengthening mechanisms:solid solution and work hardening, as well as dispersed particle and precipitation hardening. The commonly used solid-solution hardening elements are zinc, nickel, manganese, aluminum, tin, and silicon, listed in approximate order of increasing effectiveness. Commercial alloys represent the entire range of available solid-solution compositions of each element up to 35% Zn, and up to (and even beyond) 50%Ni, 50% Mn, 9% Al, 11% Sn, and 4% Si. The relative amount of solution strengthening obtained from each element or particular combination of elements is determined by the ability of the solute to interfere with dislocation motion and is reflected in the work-hardening rate starting with the annealed condition, as illustrated by the increase in tensile strength with cold work shown in Fig. 3.

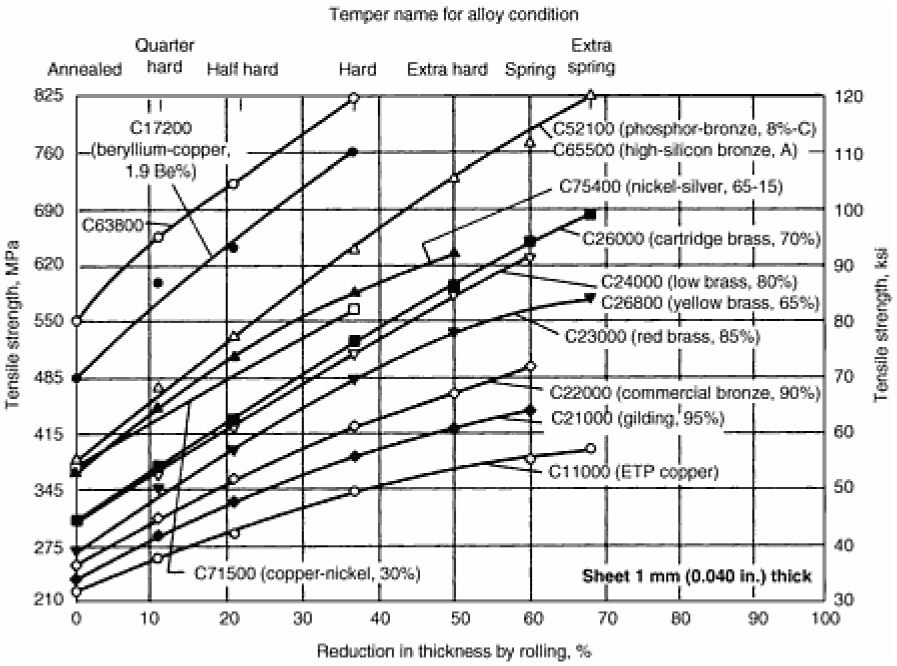


Fig. 3 Tensile strength of single-phase copper alloys as affected by percentage reduction in thickness by rolling (temper). Curves of lesser slope indicate a low rate of work hardening and a higher capacity for redrawing. ETP, electrolytic tough pitch

Work hardening is the principal hardening mechanism applied to most copper alloys, the degree of which depends on the type and amount of alloying element and whether the alloying element remains in solid solution or forms a dispersoid or precipitate phase. Even those alloys that are commercially age hardenable are often provided in the mill hardened tempers; that is, they have been processed with cold work preceding and/or following an age-hardening heat treatment. For the leaner alloys (below ∼12%Zn, or ∼3% Al, for example), processing generates dislocations that develop into entanglements and into cells, with some narrow shear band formation beyond ∼65%cold reduction in thickness. After ∼ 90% cold work, the distinct "copper"or "metal" deformation crystallographic texture begins to develop. With the richer solid-solution alloys that lower the stacking-fault energy, planar slip is the dominant dislocation mechanism, with associated higher work hardening. Beyond ∼40% cold work in these richer alloys, stacking faults, shear banding, and deformation twinning become important deformation mechanisms that, beyond 90% cold work, lead to the "brass" or"alloy" type of crystallographic deformation texture and accompanying anisotropy of properties. Figure 4shows the variation in tensile properties with cold working of an annealed Cu-30Zn alloy (C26000). The degree of work hardening seen with cold working several selected single-phase copper alloys is illustrated by the cold-rolling curves in Fig. 3. Many copper alloys are used in wrought forms in a worked temper, chosen for the desired combination of work-hardened strength and formability, either for direct use in service or for subsequent component fabrication.

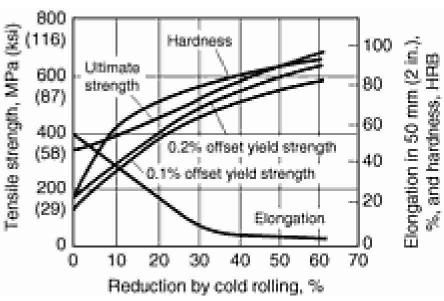


Fig. 4 The effect of cold rolling on the strength, hardness, and ductility of annealed copper alloy C26000 when it is cold rolled in varying amount up to 62% reduction in thickness.

Dispersion strengthening is used in copper alloys for hardening, controlling grain size, and providing softening resistance, as exemplified by iron particles in copper-iron alloys, C19200 or C19400, and in aluminum bronzes, C61300 or C63380. Cobalt silicide particles in alloy C63800 (Cu-2.8Al-1.8Si-0.4Co), for example, provide fine-grain control and dispersion hardening to give this alloy high strength with reasonably good formability. Alloy C63800 offers an annealed tensile strength of 570 MPa (82 ksi) and rolled temper tensile strengths of 660 to 900 MPa (96 to 130 ksi). Alloys offering exceptionally good thermal stability have been developed using powder metallurgy (P/M) techniques to incorporate dispersions of fine Al_2O_3 particles (3 to 12 nm in size) in a basic copper matrix, which is finish processed to rod, wire, or strip products. This family of alloys, C15715 to C15760, can resist softening up to and above 800 °C(1472 °F). More detailed information on oxide-dispersion-strengthened copper alloys is found in the article "Copper Powder Metallurgy Products" in this Section.

Precipitation Hardening. Age-hardening mechanisms are used in those few but important copper systems that offer a decreasing solubility for hardening phases. The beryllium-copper system offers a series of wrought and cast age-hardening alloys, UNS C17000 to C17530 and C82000 to C82800. The wrought alloys contain 0.2 to 2.0% Be and 0.3 to 2.7%Co (or up to 2.2% Ni). They are solution heat treated in the 760 to 955 °C(1400 to 1750 °F) range and age hardened to produce the beryllium-rich coherent precipitates when aged in the 260 to 565 °C (500 to 1050 °F)range, with the specific temperature being chosen for the particular alloy and desired property combination (Fig. 5). The precipitation sequence during aging consists of the formation of solute-rich G-P zones, followed in sequence by coherent platelets of the metastable intermediate phases γ' and γ". Overaging is marked by the appearance of the B2 ordered equilibrium γ-BeCu phase as particles within grains and along grain boundaries, large enough to be seen in the light microscope. The cobalt and nickel additions form dispersoids of equilibrium (Cu, Co, or Ni)Be that restrict grain growth during solution annealing in the two-phase field at elevated temperatures (Fig. 5b). A cold-working step following solution annealing is often used to increase the age-hardening response. Alloy C17200 (Cu-1.8Be-0.4Co), for example, can be processed to reach high strength; that is, tensile strengths after solutionization (470 MPa, or 68 ksi), after cold rolling to the hard temper (755 MPa, or 110 ksi) and after aging (1415 MPa, or 205 ksi). While they are commercially available in the heat-treatable (solutionized) condition, the beryllium-copper alloys are commonly provided in the mill-hardened temper with the optimal strength/ductility/conductivity combination suitable for the application.

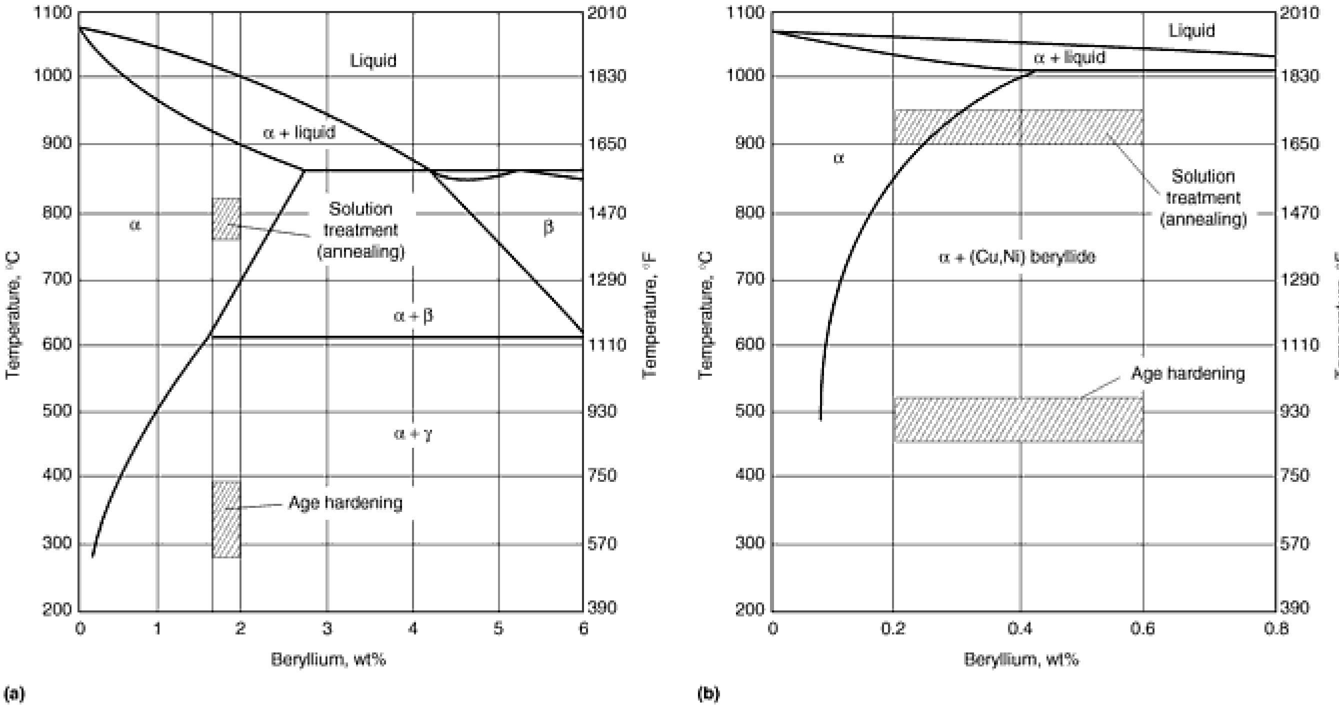


Fig. 5 Phase diagrams for beryllium-copper alloys. (a)Binary composition for high-strength alloys such as C17200. (b) Pseudobinary composition for C17510, a high-conductivity alloy

Other age-hardening copper alloys include the chromium coppers, which contain 0.4 to 1.2% Cr (C18100, C18200, and C18400); these alloys produce arrays of pure chromium precipitates and dispersoid particles when aged. The Cu-Ni-Si alloys, C64700 and C70250, age harden by precipitating the Ni_2Si intermetallic phase. Compositions in the Cu-Ni-Sn system, C71900 and C72700, are hardenable by spinodal decomposition, a mechanism that provides high strength and good ductility through the formation of a periodic array of coherent, fcc solid-solution phases that require the electron microscope to be seen. Each of these alloys, including the beryllium-coppers can be thermomechanically processed to provide unique combinations of strength, formability, electrical conductivity, softening resistance, and stress-relaxation resistance.

Copper Casting Alloys

The copper casting alloys are generally similar to the wrought counterparts, but they do offer their own unique composition/property characteristics. For example, they do offer the opportunity to add lead to levels of 25% that could not be easily made by wrought techniques in order to provide compositions in which dispersions of lead particles are useful for preventing galling in bearing applications. The copper casting alloys are used for their corrosion resistance and their high-thermal and electrical conductivity. The most common alloys are the general-purpose Cu-5Sn-5Pb-5Zn alloy (C83600), used for valves and plumbing hardware, and C84400, widely used for cast plumbing system components. C83600 contains lead particles dispersed around the single-phase matrix and offers good machinability, with moderate levels of corrosion resistance, tensile strength (240 MPa, or 35 ksi), ductility, and conductivity (15% IACS).

While the Cu-Sn-PB-(and/or Zn) casting alloys have only moderate strength, the cast manganese and aluminum bronzes offer higher tensile strengths, 450 to 900 MPa (65 to 130 ksi). As with the wrought alloys, the cast aluminum-bronze alloys commonly contain an iron addition (0.8 to 5.0%) to provide iron-rich particles for grain refinement and added strength. In addition, at aluminum levels in the 9.5 to 10.5% range (or 8.0 to 9.5% Al with nickel or manganese additions) the alloys are heat treatable for added strength. Depending on the section thickness and cooling rate of the casting, as well as the alloy composition and heat treatments, the microstructures can be rather complex. The aluminum-bronzes can be annealed completely or partially in the β field and quenched to form β martensite with α needles. Aging these alloys will temper the martensite by precipitation fine α needles. One of the aluminum-bronze alloys, Cu-10.5Al-5Fe-5Ni, for example, is used for the combination of high strength and good corrosion resistance. Through heat treatment, the intermetallic κ-phase, with a complex composition(iron, nickel, copper) aluminum and CsCl crystal structure, provides a strengthening component in any of the morphologies: as globular particles, fine precipitates, or as a component of cellular eutectoid colonies.

Table 8 lists the chemical compositions, uses, and characteristics of copper alloy castings. Additional information, including mechanical property data, is found in the article "Copper Alloy Castings" in this Section.

Table 8 Compositions, uses, and characteristics of copper alloy castings

UNS No.	Other designations, descriptive names (former SAE No.)	Applicable casting processes[a]	Composition[b], wt%						
			Cu	**Sn**	**Pb**	**Zn**	**Ni**	**Fe**	**Other**
Coppers: **High purity coppers with excellent electrical and thermal conductivities. Deoxidation of C81200 improves weldability.**									
C80100	Oxygen-free copper	S, C, CL, PM, I, P	99.95[c]	. . .	. . .	. . .	. . .	. . .	. . .
C81100	High conductivity copper	S, C, CL, PM, I, P	99.70[c]	. . .	. . .	. . .	. . .	. . .	. . .
C81200	High conductivity copper	S, C, CL, PM, I, P	99.9[c]	. . .	. . .	. . .	. . .	. . .	0.045-0.065 P
High-copper alloys: **Relatively high strength coppers with good electrical and thermal conductivity. Strength generally inversely proportional to conductivities. Used where good combination of strength and conductivity is needed, as in resistance welding electrodes, switch blades and components, dies, clutch rings, brake drums, as well as bearings and bushings. Beryllium coppers**									

have highest strength of all copper alloys and are used in bearings, mechanical products, and nonsparking safety tools.									
C81400	70C	S, C, CL, PM, I, P	98.5 min(d)	. . .	. . .	. . .	. . .	. . .	0.02-0.10 Be, 0.6-1.0 Cr
C81500	Chromium copper	S, C, CL, PM, I, P	98.0 min(d)	0.10	0.02	0.10	. . .	0.10	0.15 Si, 0.10 Al, 0.40-1.5 Cr
C81540	Chromium copper	S, C, CL, PM, I, P	95.1 min(d)(e)	0.10	0.02	0.10	2.0-3.0(f)	0.15	0.40-0.8Si, 0.10 Al, 0.10-0.6 Cr
C82000	10C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.10	0.10 Al, 0.10 Cr, 0.15 Si, 2.40-2.70 Co(f), 0.45-0.8 Be
C82200	35C, 53B	S, C, CL, PM, I, P	bal(d)	. . .	. . .	. . .	1.0-2.0	. . .	0.35-0.80 Be, 0.30 Co
C82400	165C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.20	0.20-0.65 Co, 1.60-1.85 Be, 0.15Al, 0.10 Cr
C82500	20C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.25	1.90-2.25 Be, 0.35-0.70 Co(f), 0.20-0.35 Si, 0.15Al, 0.10 Cr
C82510	Increased-Co 20C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.25	1.90-2.15 Be, 1.0-1.2 Co(f), 0.20-0.35 Si, 0.15 Al, 0.10 Cr
C82600	245C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.25	2.25-2.55 Be, 0.35-0.65 Co, 0.20-0.35 Si, 0.15 Al, 0.10 Cr
C82700	Nickel-beryllium copper	S, C, CL, PM, I, P	bal(d)	0.10	0.02	0.10	1.0-1.5	0.25	2.35-2.55 Be, 0.15 Si, 0.15 Al, 0.10 Cr
C82800	275C	S, C, CL, PM, I, P, D	bal(d)	0.10	0.02	0.10	0.20	0.25	2.50-2.85 Be, 0.35-0.70 Co(f), 0.20-0.35 Si, 0.15 Al, 0.10 Cr
Copper-tin-zinc and copper-tin-zinc-lead alloys (red and leaded red brasses): **High-copper brasses with reasonable electrical conductivity and moderate strength. Used for electrical hardware, including cable connectors.**									
C83300	131, contact metal	S, C, CL	92.0-94.0(g)(h)	1.0-2.0	1.0-2.0	2.0-6.0	. . .	. . .	. . .

C83400	407.5, commercial bronze 90/10, gilding metal	S, C, CL	88.0-92.0(g)(h)	0.20	0.50	8.0-12.0	1.0	0.25	0.25 Sb, 0.08 S, 0.03 P, 0.005 Si, 0.005 Al
C83450	Nickel-bearing leaded red brass	S, C, CL	87.0-89.0(g)(h)	2.0-3.5	1.5-3.0	5.5-7.5	0.8-2.0(i)	0.30	0.25 Sb, 0.08 S, 0.03 P(j), 0.005 Al, 0.005 Si
C83500	Leaded nickel-bearing tin bronze	S, C, CL	86.0-88.0(g)(h)	5.5-6.5	3.5-5.5	1.0-2.5	0.50-1.0(i)	0.25	0.25 Sb, 0.08 S, 0.03(j), 0.005 Al, 0.005 Si
Copper-tin-zinc and copper-tin-zinc-lead alloys (red and leaded red brasses): **Good corrosion resistance, excellent castability and moderate strength. Lead content ensures pressure tightness. Alloy C83600 is one of the most important cast alloys, widely used for plumbing fittings and other water-service goods. Alloy C83800 has slightly lower strength, but is essentially similar in properties and application.**									
C83600	115, 85-5-5-5, composition bronze, ounce metal, (SAE 40)	S, C, CL	84.0-86.0(g)(h)	4.0-6.0	4.0-6.0	4.0-6.0	1.0(i)	0.30	0.25 Sb, 0.08 S, 0.05 P(j), 0.005 Al, 0.005 Si
C83800	120, 83-4-6-7, commercial red brass, hydraulic bronze	S, C, CL	82.0-83.8(g)(h)	3.3-4.2	5.0-7.0	5.0-8.0	1.0(i)	0.30	0.25 Sb, 0.08 S, 0.03 P(j), 0.005 Al, 0.005 Si
C83810	Nickel-bearing leaded red brass	S, C, CL	bal(g)(h)	2.0-3.5	4.0-6.0	7.5-9.5	2.0(i)	0.50(k)	Sb(k), As(k), 0.005 Al, 0.10 Si
Copper-tin-zinc-lead alloys (leaded semired brasses): **General purpose alloys for plumbing and hardware goods. Good machinability and pressure tightness. Alloy C84400 is the most popular plumbing alloy in U.S. markets.**									
C84200	101, 80-5-2½-12½	S, C, CL	78.0-82.0(g)(h)	4.0-6.0	2.0-3.0	10.0-16.0	0.8(i)	0.40	0.25 Sb, 0.08 S, 0.05 P(j), 0.005 Al, 0.005 Si
C84400	123, 81-3-7-9, valve composition, 81 metal	S, C, CL	78.0-82.0(g)(h)	2.3-3.5	6.0-8.0	7.0-10.0	1.0(i)	0.40	0.25 Sb, 0.08 S, 0.02 P(j), 0.005 Al, 0.005 Si
C84410	. . .	S, C, CL	bal(g)(l)	3.0-4.5	7.0-9.0	7.0-11.0	1.0(i)	(m)	Sb(m), 0.01 Al, 0.20 Si, 0.05 Bi
C84500	125, 78 metal	S, C, CL	77.0-79.0(g)(h)	2.0-4.0	6.0-7.5	10.0-14.0	1.0(i)	0.40	0.25 Sb, 0.08 S, 0.02 P(j), 0.005 Al, 0.005 Si
C84800	130, 76-3-6-15, 76 metal	S, C, CL	75.0-77.0(g)(h)	2.0-3.0	5.5-7.0	13.0-17.0	1.0(i)	0.40	0.25 Sb, 0.08 S, 0.02 P(j), 0.005 Al, 0.005 Si
Copper-zinc and copper-zinc-lead alloys (yellow and leaded yellow brasses): **Low-cost, low-to-moderate strength, general-purpose**									

casting alloys with good machinability, adequate corrosion resistance for many water-service applications including marine hardware and automotive cooling systems. Some compositions are amenable to permanent mold and die casting processes.									
C85200	400, 72-1-3-24, high copper yellow brass	S, C, CL	70.0-74.0(g)(n)	0.7-2.0	1.5-3.8	20.0-27.0	1.0(i)	0.6	0.20 Sb, 0.05 S, 0.02 P, 0.005 Al, 0.05 Si
C85400	403, 67-1-3-29, commercial No. 1 yellow brass	S, C, CL, PM, I, P	65.0-70.0(g)(s)	0.50-1.5	1.5-3.8	24.0-32.0	1.0(i)	0.7	0.35 Al, 0.05 Si
C85500	60-40 yellow brass	S, C, CL	59.0-63.0(g)(s)	0.20	0.20	bal	0.20(i)	0.20	0.20 Mn
C85700	405.2, 63-1-1-35, B2, permanent mold brass	S, C, CL, PM, I, P	58.0-64.0(g)(n)	0.50-1.5	0.80-1.5	32.0-40.0	1.0(i)	0.7	0.8 Al, 0.05 Si
C85800	405.1, die casting yellow brass	S, C, CL, PM, I, P, D	57.0 min(g)(s)	1.5	1.5	31.0-41.0	0.50(i)	0.50	0.05 Sb, 0.25 Mn, 0.05 As, 0.05 S, 0.01 P, 0.55 Al, 0.25 Si
Manganese bronze and leaded manganese bronze alloys (high strength and leaded high strength yellow brasses):**Alloys with high mechanical strength, good corrosion resistance and favorable castability. Can be machined, but with the exception of C86400 and C86700, are less readily machined than leaded compositions. Alloy C86300 can attain tensile strengths exceeding 115 ksi (793 MPa). Used for mechanical devices:gears, levers, brackets, and valve and pump components for fresh and seawater service. When used for high strength bearings, alloys C86300 and C86400 require hardened shafts.**									
C86100	423, 90,000 tensile manganese bronze	S, CL, PM, I, P	66.0-68.0(g)(o)	0.20	0.20	bal	. . .	2.0-4.0	4.5-5.5 Al, 2.5-5.5 Mn
C86200	423, 95,000 tensile manganese bronze, (SAE 430 A)	S, C, CL, PM, I, P, D	60.0-66.0(g)(o)	0.20	0.20	22.0-28.0	1.0(i)	2.0-4.0	3.0-4.9 Al, 2.5-5.0 Mn
C86300	424, 110,000 tensile manganese bronze, (SAE 430B)	S, C, CL, PM, I, P	60.0-66.0(g)(o)	0.20	0.20	22.0-28.0	1.0(i)	2.0-4.0	5.0-7.5 Al, 2.5-5.0 Mn
C86400	420, 60,000 tensile manganese bronze	S, C, CL, PM, I, P, D	56.0-62.0(g)(o)	0.50-1.5	0.50-1.5	34.0-42.0	1.0(i)	0.40-2.0	0.50-1.5 Al, 0.10-1.5 Mn
C86500	421, 65,000 tensile manganese bronze, (SAE 43)	S, C, CL, PM, I, P	55.0-60.0(e)(m)	1.0	0.40	36.0-42.0	1.0(i)	0.40-2.0	0.50-1.5 Al, 0.10-1.5 Mn
C86700	422, 80,000 tensile manganese bronze	S, C, CL, PM, I, P	55.0-60.0(g)(o)	1.5	0.50-1.5	30.0-38.0	1.0(i)	1.0-3.0	1.0-3.0 Al, 0.10-3.5 Mn
C86800	Nickel-manganese bronze	S, C, CL, PM, I, P	53.5-57.0(g)(o)	1.0	0.20	bal	2.5-4.0(i)	1.0-2.5	2.0 Al, 2.5-4.0 Mn

Copper-silicon alloys (silicon bronzes and silicon brasses): **Moderate-to-high strength alloys with good corrosion resistance and favorable casting properties. Used for mechanical products and pump components where combination of strength and corrosion resistance is important. Similar compositions are commonly die and/or permanent mold cast in Europe and the United Kingdom.**									
C87300	95-1-4, silicon bronze	S, C, CL, PM, I, P	94.0 min(d)	. . .	0.20	0.25	. . .	0.20	3.5-4.5 Si, 0.80-1.5 Mn
C87400	500	S, CL, PM, I, P, D	79.0 min(d)	. . .	1.0	12.0-16.0	. . .	. . .	0.80 Al, 2.5-4.0 Si
C87500	500	S, CL, PM, I, P, D	79.0 min(d)	. . .	0.50	12.0-16.0	. . .	. . .	0.50 Al, 3.0-5.0 Si
C87600	500, low zinc silicon brass	S, CL, PM, I, P, D	88.0 min(d)	. . .	0.50	4.0-7.0	. . .	0.20	3.5-5.5 Si, 0.25 Mn
C87610	. . .	S, CL, PM, I, P, D	90.0 min(d)	. . .	0.20	3.0-5.0	. . .	0.20	3.0-5.0 Si, 0.25 Mn
C87800	500, die cast silicon brass	S, CL, PM, I, P, D	80.0 min(d)	0.25	0.15	12.0-16.0	0.20(i)	0.15	0.15 Al, 3.8-4.2 Si, 0.15 Mn, 0.01 Mg, 0.05 S, 0.01 P, 0.05 As, 0.05 Sb
Copper-tin alloys (tin bronzes): **Hard, strong alloys with good corrosion resistance, especially against seawater. As bearings, they are wear resistant and resist pounding well. Moderately machinable. Widely used for gears, wormwheels, bearings, marine fittings, piston rings, and pump components.**									
C90200	242, 93-7-0-0	S, C, CL, PM, I, P	91.0-94.0(g)(p)	6.0-8.0	0.30	0.50	0.50(i)	0.20	0.20 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C90300	225, 88-8-0-4, Navy "G" bronze, (SAE 620)	S, C, CL, PM, I, P	86.0-89.0(g)(p)	7.5-9.0	0.30	3.0-5.0	1.0(i)	0.20	0.20 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C90500	210, 88-10-0-2, gun metal, (SAE 62)	S, C, CL, PM, I, P	86.0-89.0(g)(y)	9.0-11.0	0.30	1.0-3.0	1.0(i)	0.20	0.20 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C90700	205, 89-11, (SAE 65)	S, C, CL, PM, I, P	88.0-90.0(g)(p)	10.0-12.0	0.50	0.50	0.50(i)	0.15	0.20 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
C90710	. . .	S, C, CL, PM, I, P	bal(g)(p)	10.0-12.0	0.25	0.05	0.10(i)	0.10	0.20 Sb, 0.05 S, 0.05-1.2 P(j), 0.005 Al, 0.005 Si
C90800	. . .	S, C, CL,	85.0-	11.0-	0.25	0.25	0.50(i)	0.15	0.20 Sb, 0.05 S, 0.30 P(j), 0.005 Al,

		PM, I, P	89.0(g)(p)	13.0					0.005 Si
C90810	. . .	S, C, CL, PM, I, P	bal(g)(p)	11.0-13.0	0.25	0.30	0.50(i)	0.15	0.20 Sb, 0.05 S, 0.15-0.8 P(j), 0.005 Al, 0.005 Si
C90900	199, 87-13-0-0	S, C, CL, PM, I, P	86.0-89.0(g)(p)	12.0-14.0	0.25	0.25	0.50(i)	0.15	0.20 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C91000	197, 85-14-0-1	S, C, CL, PM, I, P	84.0-86.0(g)(p)	14.0-16.0	0.20	1.5	0.80(i)	0.10	0.20 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C91100	84-16-0-0	S, C, CL, PM, I, P	82.0-85.0(g)(p)	15.0-17.0	0.25	0.25	0.50(i)	0.25	0.20 Sb, 0.05 S, 1.0 P(j), 0.005 Al, 0.005 Si
C91300	194, 81-19	S, C, CL, PM, I, P	79.0-82.0(g)(p)	18.0-20.0	0.25	0.25	0.50(i)	0.25	0.20 Sb, 0.05 S, 1.0 P(j), 0.005 Al, 0.005 Si
C91600	205N, 88-10½-0-0-1½, nickel gear bronze	S, C, CL, PM, I, P	86.0-89.0(g)(p)	9.7-10.8	0.25	0.25	1.2-2.0(i)	0.20	0.20 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
C91700	86½-12-0-0-1½, nickel gear bronze	S, C, CL, PM, I, P	84.0-87.0(g)(p)	11.3-12.5	0.25	0.25	1.20-2.0(i)	0.20	0.20 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
Copper-tin-lead alloys (leaded tin bronzes): **Lead improves machinability in these tin bronzes but does not materially affect mechanical properties. The alloys are essentially free-cutting versions of the tin bronzes, above, and have similar properties and uses.**									
C92200	245, 88-6-1½-4½, Navy "M" bronze, steam bronze,(SAE 622)	S, C, CL, PM, I, P	86.0-90.0(g)(h)	5.5-6.5	1.0-2.0	3.0-5.0	1.0(i)	0.25	0.25 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C92210	. . .	. . .	86.0-89.0(g)(h)	4.5-5.5	1.7-2.5	3.0-4.5	0.7-1.0	0.25	0.25 Sb, 0.05 S, 0.03 P, 0.005 Al, 0.005 Si
C92300	230, 87-8-1-4, leaded "G" bronze	S, C, CL, PM, I, P	85.0-89.0(g)(h)	7.5-9.0	0.30-1.0	2.5-5.0	1.0(i)	0.25	0.25 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C92310	. . .	S, C, CL, PM, I, P	bal(g)(h)	7.5-8.5	0.30-1.5	3.5-4.5	1.0(i)	. . .	0.03 Mn, 0.005 Al, 0.005 Si

C92400	. . .	S, C, CL, PM, I, P	86.0-89.0(g)(h)	9.0-11.0	1.0-2.5	1.0-3.0	1.0(i)	0.25	0.25 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C92410	. . .	S, C, CL, PM, I, P	bal(g)(h)	6.0-8.0	2.5-3.5	1.5-3.0	0.20(i)	0.20	0.25 Sb, 0.05 Mn, 0.005 Al, 0.005 Si
C92500	200, 87-11-1-0-1, (SAE 640)	S, C, CL, PM, I, P	85.0-88.0(g)	10.0-12.0	1.0-1.5	0.50	0.8-1.5(i)	0.30	0.25 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
C92600	215, 87-10-1-2	S, C, CL, PM, I, P	86.0-88.50(g)(h)	9.3-10.5	0.8-1.5	1.3-2.5	0.7(i)	0.20	0.25 Sb, 0.05 S, 0.03 P(j), 0.005 Al, 0.005 Si
C92610	. . .	S, C, CL, PM, I, P	bal(g)(h)	9.5-10.5	0.30-1.5	1.7-2.8	1.0(i)	0.15	0.005 Al, 0.005 Si, 0.03 Mn
C92700	206, 88-10-2-0, (SAE 63)	S, C, CL, PM, I, P	86.0-89.0(g)(h)	9.0-11.0	1.0-2.5	0.7	1.0(i)	0.20	0.25 Sb, 0.05 S, 0.25 P(j), 0.005 Al, 0.005 Si
C92710	. . .	S, C, CL, PM, I, P	bal(g)(h)	9.0-11.0	4.0-6.0	1.0	2.0(i)	0.20	0.25 Sb, 0.05 S, 0.10 P(j), 0.005 Al, 0.005 Si
C92800	295, 79-16-5-0 ring metal	S, C, CL, PM, I, P	78.0-82.0(g)(h)	15.0-17.0	4.0-6.0	0.8	0.80(i)	0.20	0.25 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C92810	. . .	S, C, CL, PM, I, P	78.0-82.0(g)	12.0-14.0	4.0-6.0	0.50	0.8-1.2(i)	0.50	0.25 Sb, 0.05 S, 0.05 P(j), 0.005 Al, 0.005 Si
C92900	84-10-2 $\frac{1}{2}$ -0-3 $\frac{1}{2}$, leaded nickel tin bronze	S, C, CL, PM, I, P	82.0-86.0(g)	9.0-11.0	2.0-3.2	0.25	2.8-4.0(i)	0.20	0.25 Sb, 0.05 S, 0.50 P(j), 0.005 Al, 0.005 Si
Copper-tin-lead alloys (high leaded tin bronzes): **Most commonly used bearing alloys, found in bearings operating at moderate-to-high speeds, as in electric motors and appliances. Alloy C93200 is considered the workhorse alloy of the series. Alloy C93600 has improved machining and anti-seizing properties. C93800 noted for good corrosion resistance against concentrations of sulfuric acid below 78%. Alloy C94100 is especially good under boundary lubricated conditions.**									
C93100	. . .	S, C, CL, PM, I, P	bal(g)(o)	6.5-8.5	2.0-5.0	2.0	1.0(i)	0.25	0.25 Sb, 0.05 S, 0.30 P(j), 0.005 Al, 0.005 Si
C93200	315, 83-7-7-3, bearing bronze, (SAE 660)	S, C, CL, PM, I, P	81.0-85.0(g)(o)	6.3-7.5	6.0-8.0	1.0-4.0	1.0(i)	0.20	0.35 Sb, 0.08 S, 0.15 P(j), 0.005 Al, 0.005 Si

C93400	311, 84-8-8-0	S, C, CL, PM, I, P	82.0-85.0(g)(o)	7.0-9.0	7.0-9.0	0.8	1.0(i)	0.20	0.50 Sb, 0.08 S, 0.50 P(j), 0.005 Al, 0.005 Si
C93500	326, 85-5-9-1, (SAE 66)	S, C, CL, PM, I, P	83.0-86.0(g)(o)	4.3-6.0	8.0-10.0	2.0	1.0(i)	0.20	0.30 Sb, 0.08 S, 0.05 P(j), 0.005 Al, 0.005 Si
C93600	. . .	S, C, CL, PM, I, P	79.0-83.0(h)	6.0-8.0	11.0-13.0	1.0	1.0(i)	0.20	0.55 Sb, 0.08 S, 0.15 P(j), 0.005 Al, 0.005 Si
C93700	305, 80-10-10, bushing and bearing bronze, (SAE 64)	S, C, CL, PM, I, P	78.0-82.0(o)	9.0-11.0	8.0-11.0	0.8	0.50(i)	0.7(q)	0.50 Sb, 0.08 S, 0.10 P(j), 0.005 Al, 0.005 Si
C93720	. . .	S, C, CL, PM, I, P	83.0 min(o)	3.5-4.5	7.0-9.0	4.0	0.50(i)	0.7	0.50 Sb, 0.10 P(j)
C93800	319, 78-7-15, anti-acid metal, (SAE 67)	S, C, CL, PM, I, P	75.0-79.0(o)	6.3-7.5	13.0-16.0	0.8	1.0(i)	0.15	0.8 Sb, 0.08 S, 0.05 P(j), 0.005 Al, 0.005 Si
C93900	79-6-15	S, C, CL, PM, I, P	76.5-79.5(r)	5.0-7.0	14.0-18.0	1.5	0.8(i)	0.40	0.50 Sb, 0.08 S, 1.5 P(j), 0.005 Al, 0.005 Si
C94000	. . .	S, C, CL, PM, I, P	69.0-72.0(s)	12.0-14.0	14.0-16.0	0.50	0.50-1.0(i)	0.25	0.50 Sb, 0.08 S(t), 0.05 P(j), 0.005 Al, 0.005 Si
C94100	. . .	S, C, CL, PM, I, P	72.0-79.0(s)	4.5-6.5	18.0-22.0	1.0	1.0(i)	0.25	0.8 Sb, 0.08 S(t), 0.05 P(j), 0.005 Al, 0.005 Si
C94300	. . .	S, C, CL, PM, I, P	67.0-72.0(o)	4.5-6.0	23.0-27.0	0.8	1.0(i)	0.15	0.80 Sb, 0.08 S(t), 0.08 P(j), 0.005 Al, 0.005 Si
C94310	. . .	S, C, CL, PM, I, P	bal(o)	1.50-3.0	27.0-34.0	0.50	0.25-1.0(i)	0.50	0.50 Sb, 0.05 P(j)
C94320	. . .	S, C, CL, PM, I, P	bal(o)	4.0-7.0	24.0-32.0	. . .	. . .	0.35	. . .
C94330	. . .	S, C, CL, PM, I, P	68.5-75.5(o)	3.0-4.0	21.0-25.0	3.0	0.50(i)	0.7	0.50 Sb, 0.10 P(j)
C94400	312, 81-8-11, phosphor bronze	S, C, CL, PM, I, P	bal(o)	7.0-9.0	9.0-12.0	0.8	1.0(i)	0.15	0.8 Sb, 0.08 S, 0.50 P(j), 0.005 Al,

									0.005 Si
C94500	321, 73-7-20, medium bronze	S, C, CL, PM, I, P	bal(o)	6.0-8.0	16.0-22.0	1.2	1.0(i)	0.15	0.80 Sb, 0.08 S, 0.05 P, 0.005 Al, 0.005 Si
Copper-tin-nickel alloys (nickel-tin bronzes): **High strength structural castings. Easy to cast, pressure tight. Corrosion and wear resistant. C94700 is heat treatable. Alloys used for bearings, worm gears, valve stems and nuts, impellers, screw conveyors, roller bearing cages, and railway electrification hardware.**									
C94700	88-5-0-2-5	S, C, CL, PM, I, P	85.0-90.0(s)	4.5-6.0	0.10(u)	1.0-2.5	4.5-6.0(i)	0.25	0.15 Sb, 0.20 Mn, 0.05, S 0.05 P, 0.005 Al, 0.005 Si
C94800	87-5-1-2-5, leaded nickel-tin bronze	S, C, CL, PM, I, P	84.0-89.0(s)	4.5-6.0	0.30-1.0	1.0-2.5	4.5-6.0(i)	0.25	0.15 Sb, 0.20 Mn, 0.05 S, 0.05 P, 0.005 Al, 0.005 Si
C94900	Leaded nickel-tin bronze	S, C, CL, PM, I, P	79.0-81.0(p)	4.0-6.0(i)	4.0-6.0	4.0-6.0	4.0-6.0(i)	0.30	0.25 Sb, 0.10 Mn, 0.08 S, 0.05 P, 0.005 Al, 0.005 Si
Copper-aluminum-iron and copper-aluminum-iron-nickel alloys (aluminum bronzes): **The aluminum bronzes are characterized by high strength and excellent corrosion resistance. Alloys containing more than 9.5% Al can be heat treated, some to tensile strengths exceeding 120 ksi (827 MPa). Uses include a variety of heavy duty mechanical and structural products including gears, worm drives, valve guides, and seats. Excellent heavy duty bearing alloys, but do not tolerate misalignment or dirty lubricants, and generally should be used against hardened steel shafts, with both shaft and bearing machined to fine surface finishes.**									
C95200	415, 88-3-9 aluminum bronze 9A, (SAE 68a)	S, C, CL, PM, I, P	86.0 min(o)	. . .	. . .	. . .	. . .	2.5-4.0	8.5-9.5 Al
C95210	. . .	S, C, CL, PM, I, P	86.0 min(o)	0.10	0.05	0.50	1.0(i)	2.5-4.0	8.5-9.5 Al, 1.0 Mn, 0.05 Mg, 0.25 Si
C95220	. . .	S, C, CL, PM, I, P	bal(d)	. . .	. . .	. . .	2.5(i)	2.5-4.0	9.5-10.5 Al, 0.50 Mn
C95300	415, 89-1-10, aluminum bronze 9B, (SAE 68b)	S, C, CL, PM, I, P	83.0 min(o)	. . .	. . .	. . .	. . .	0.8-1.5	9.0-11.0 Al
C95400	415, 85-4-11, aluminum bronze 9C	S, C, CL, PM, I, P	83.0 min(d)	. . .	. . .	. . .	1.5(i)	3.0-5.0	10.0-11.5 Al, 0.50 Mn
C95410	. . .	S, C, CL, PM, I, P	83.0 min(d)	. . .	. . .	. . .	1.5-2.5(i)	3.0-5.0	10.0-11.5 Al, 0.50 Mn
C95420	. . .	S, C, CL, PM, I, P	83.5 min(d)	. . .	. . .	. . .	0.50(i)	3.0-4.3	10.5-12.0 Al, 0.50 Mn

C95500	415, 81-4-4-11, aluminum bronze 9D	S, C, CL, PM, I, P	78.0 min[(d)]	. . .	. . .	. . .	3.0-5.5[(i)]	3.0-5.0	10.0-11.5 Al, 3.5 Mn
C95510	Nickel-aluminum bronze	S, C, CL, PM, I, P	78.0 min[(v)]	0.20	. . .	0.30	4.5-5.5[(i)]	2.0-3.5	9.7-10.9 Al, 1.5 Mn
C95520	Nickel-aluminum bronze	S, C, CL, PM, I, P	74.5 min[(d)]	0.25	0.03	0.30	4.2-6.0[(i)]	4.0-5.5	10.5-11.5 Al, 1.5 Mn, 0.15 Si, 0.20 Co, 0.05 Cr
C95600	91-2-7, aluminum-silicon bronze	S, C, CL, PM, I, P	88.0 min[(o)]	. . .	. . .	. . .	0.25[(i)]	. . .	6.0-8.0 Al, 1.8-3.2 Si
C95700	75-3-8-2-12, manganese-aluminum bronze	S, C, CL, PM, I, P	71.0 min[(d)]	. . .	. . .	. . .	1.5-3.0[(i)]	2.0-4.0	7.0-8.5 Al, 11.0-14.0 Mn, 0.10 Si
C95710	Manganese-aluminum bronze	S, C, CL, PM, I, P	71.0 min[(d)]	1.0	0.05	0.50	1.5-3.0[(i)]	2.0-4.0	7.0-8.5 Al, 11.0-14.0 Mn, 0.15 Si, 0.05 P
C95800	415, 81-5-4-9-1 alpha nickel-aluminum bronze, propeller bronze	S, C, CL, PM, I, P	79.0 min[(d)]	. . .	0.03	. . .	4.0-5.0[(i)(w)]	3.5-4.5[(w)]	8.5-9.5 Al, 0.8-1.5 Mn, 0.10 Si
C95810	Nickel-aluminum bronze	S, C, CL, PM, I, P	79.0 min[(d)]	. . .	0.10	0.50	4.0-5.0[(i)(w)]	3.5-4.5[(w)]	8.5-9.5 Al, 0.8-1.5 Mn, 0.05 Mg, 0.10 Si
C95900	. . .	S, C, CL, PM, I, P	bal[(d)]	. . .	. . .	. . .	0.50[(i)]	3.0-5.0	12.0-13.5 Al, 1.5 Mn
Copper-nickel-iron alloys (copper-nickels): **Excellent corrosion resistance, especially against seawater. High strength and toughness from low to elevated temperatures. Very widely used in marine applications, as pump and valve components, fittings, flanges, etc. Beryllium-containing alloys can be heat treated to approximately 110 ksi (758 MPa).**									
C96200	90-10 copper-nickel	S, C, CL, PM, I, P	bal[(d)]	. . .	0.01	. . .	9.0-11.0[(i)]	1.0-1.8	1.5 Mn, 0.50 Si, 0.5-1.0 Nb, 0.10 C, 0.02 S, 0.02 P
C96300	80-20 copper-nickel	S, C, CL, PM, I, P	bal[(d)]	. . .	0.01	. . .	18.0-22.0[(i)]	0.50-1.5	0.25-1.5 Mn, 0.50 Si, 0.50-1.5 Nb, 0.15 C, 0.02 S, 0.02 P
C96400	70-30 copper nickel	S, C, CL, PM, I, P	bal[(d)]	. . .	0.01	. . .	28.0-32.0[(i)]	0.25-1.5	1.5 Mn, 0.50 Si, 0.50-1.5 Nb, 0.15 C, 0.02 S, 0.02 P

C96600	717C, beryllium copper-nickel	S, C, CL, PM, I, P	bal(d)	. . .	0.01	. . .	29.0-33.0(i)	0.8-1.1	1.0 Mn, 0.15 Si, 0.40-0.7 Be
C96700	Beryllium-zirconium-titanium copper nickel	S, C, CL, PM, I, P	bal(d)	. . .	0.01	. . .	29.0-33.0(i)	0.40-0.70	0.40-0.70 Mn, 0.15 Si, 1.1-1.2 Be, 0.15-0.35 Zr, 0.15-0.35 Ti
C96800	Spinodal alloy	S, C, CL, PM, I, P	bal(d)	. . .	0.005	. . .	9.5-10.5(i)	0.50	0.05-0.30 Mn, 0.05 Si, 0.10-0.30 Nb(x)
C96900	Spinodal alloy	S, C, CL, PM, I, P	bal(d)	7.5-8.5	0.02	0.50	14.5-15.5(i)	0.50	0.05-0.30 Mn, 0.10 Nb, 0.15 Mg
Copper-nickel-zinc alloys (nickel silvers): **Moderately strong alloys with very good corrosion resistance and a pleasing silver color. Used in valves, fittings, and other components for dairy equipment and as architectural and decorative trim.**									
C97300	56-2-10-20-12, 12% nickel silver	S, C, CL, PM, I, P	53.0-58.0(o)	1.5-3.0	8.0-11.0	17.0-25.0	11.0-14.0(i)	1.5	0.35 Sb, 0.08 S, 0.05 P, 0.005 Al, 0.50 Mn, 0.15 Si
C97400	59-3-5-17-16, 15% nickel silver	S, C, CL, PM, I, P	58.0-61.0(o)	2.5-3.5	4.5-5.5	bal	15.5-17.0(i)	1.5	0.50 Mn
C97600	64-4-4-8-20, 20% nickel silver, dairy metal	S, C, CL, PM, I, P	63.0-67.0(y)	3.5-4.5	3.0-5.0	3.0-9.0	19.0-21.5(i)	1.5	0.25 Sb, 0.08 S, 0.05 P, 0.005 Al, 1.0 Mn, 0.15 Si
C97800	66-5-2-2-25, 25% nickel silver	S, C, CL, PM, I, P	64.0-67.0(z)	4.0-5.5	1.0-2.5	1.0-4.0	24.0-27.0(i)	1.5	0.20 Sb, 0.08 S, 0.05 P, 0.005 Al, 1.0 Mn, 0.15 Si
Copper-lead alloys (leaded coppers): **Ultrahigh lead alloys for special purpose bearings. Alloys have relatively low strength and poor impact properties and generally require reinforcement.**									
C98200	Leaded copper, 25% SAE 49	S, C	bal(d)	0.6-2.0	21.0-27.0	0.50	0.50	0.7	0.10 P, 0.50 Sb
C98400	Leaded copper, 30%	S, C	bal(d)	0.50	26.0-33.0	0.50	0.50	0.7	1.5 Ag, 0.10 P, 0.50 Sb
C98600	Leaded copper, 35% SAE 480	S, C	60.0-70.0	0.50	30.0-40.0	. . .	. . .	0.35	1.5 Ag
C98800	Leaded copper, 40% SAE 481	S, C	56.5-62.5(e)	0.25	37.5-42.5(aa)	0.10	. . .	0.35	5.5 Ag(aa), 0.02 P

C98820	Leaded copper, 42% SAE 484	S, C	bal	1.0-5.0	40.0-44.0	. . .	. . .	0.35	. . .
C98840	Leaded copper, 50% SAE 485	S, C	bal	1.0-5.0	44.0-58.0	. . .	. . .	0.35	. . .
Special alloys: **Alloys specifically designed for glassmaking molds, but also used for marine hardware.**									
C99300	Incramet 800	S, C, CL	bal[(y)]	0.05	0.02	. . .	13.5-16.5	0.40-1.0	10.7-11.5 Al, 1.0-2.0 Co, 0.02 Si
C99350	Copper-nickel-aluminum-zinc alloy	S, C, CL	bal[(y)]	. . .	0.15	7.5-9.5	14.5-16.0[(i)]	1.0	9.5-10.5 Al, 0.25 Mn
Special alloys: **Moderate strength alloys with good resistance to dezincification and dealuminification. Used in various products for marine (especially outboard) and mining equipment.**									
C99400	Non-dezincification alloy, NDZ	S, C, CL, I, P	bal[(y)]	. . .	0.25	0.50-5.0	1.0-3.5	1.0-3.0	0.50-2.0 Al, 0.50-2.0 Si, 0.50 Mn
C99500	Copper-nickel-aluminum-zinc-iron alloy	S, C, CL	bal[(y)]	. . .	0.25	0.50-2.0	3.5-5.5	3.0-5.0	0.50-2.0 Al, 0.50-2.0 Si, 0.50 Mn
Special alloys: **Special purpose alloys with exceptionally high damping capacity.**									
C99600	Incramute 1	S, C, CL	bal[(y)]	0.10	0.02	0.20	0.20	0.20	1.0-2.8 Al, 0.20 Co, 0.10 Si, 39.0-45.0 Mn, 0.05 C
C99700	White manganese brass	S, CL, PM, I, P, D	54.0 min[(y)]	1.0	2.0	19.0-25.0	4.0-6.0	1.0	0.50-3.0 Al, 11.0-15.0 Mn
C99750	Copper-zinc-manganese alloy	S, PM, I, P, D	55.0-61.0[(y)]	0.50-2.5	. . .	17.0-23.0	5.0	1.0	0.25-3.0 Al, 17.0-23.0 Mn

Source: Copper Development Association Inc.

(a) Casting processes: S, sand; D, die; C, continuous; I, investment; PM, permanent mold; CL, centrifugal;and P, plaster.

(b) Composition values are given as maximum percentages, unless shown as a range or minimum.

(c) Including Ag, % min.

(d) Cu + sum of named elements, 99.5%min.

(e) Includes Ag.

(f) Ni + Co.

(g) In determining copper min, copper can be calculated as Cu + Ni.

(h) Cu + sum of named elements, 99.3%min.

(i) Including Co.

(j) For continuous castings, P is 1.5% max.

(k) Fe + Sb + As is 0.50% max.

(l) Cu + sum of named elements, 99.2%min.

(m) Fe + Sb + As is 0.8% max.

(n) Cu + sum of named elements, 99.1% min.

(o) Cu + sum of named elements, 99.0% min.

(p) Cu + sum of named elements, 99.4% min.

(q) Fe is 0.35% max, when used for steel-backed bearings.

(r) Cu + sum of named elements, 98.9% min.

(s) Cu + sum of named elements, 98.7% min.

(t) For continuous castings, S is 0.25%max.

(u) The mechanical properties of C94700 (heat treated) may not be attainable if the lead content exceeds 0.01%.

(v) Cu + sum of named elements, 99.8% min.

(w) Fe content should not exceed Ni content.

(x) The following additional maximum impurity limits shall apply: 0.10% Al, 0.001%B, 0.001% Bi, 0.005-0.15% Mg, 0.005% P, 0.0025% S, 0.02% Sb, 7.5-8.5%Sn, 0.01% T, and 1.0% Zn.

(y) Cu + sum of named elements, 99.7% min.

(z) Cu + sum of named elements, 99.6% min.

(aa) Pb and Ag can be adjusted to modify the alloy hardness.

Copper Tubular Products

Introduction

TUBE AND PIPE made of copper or copper alloys are used extensively for carrying potable water in buildings and homes. These products also are used throughout the oil, chemical, and process industries to carry diverse fluids, ranging from various natural and process waters, to seawater, to an extremely broad range of strong and dilute organic and inorganic chemicals. In the automotive and aerospace industries, copper tube is used for hydraulic lines, heat exchangers (such as automotive radiators), air conditioning systems, and various formed or machined fittings. In marine service, copper tube and pipe are used to carry potable water, seawater, and other fluids, but their chief application is in tube bundles for condensers, economizers, and auxiliary heat exchangers. Copper tube and pipe are used in food and beverage industries to carry process fluids for beet and cane sugar refining, for brewing of beer, and for many other food-processing operations. In the building trades, copper tube is used widely for heating and air conditioning systems in homes, commercial buildings, and industrial plants and offices. Table 1 summarizes selected copper alloys that are standard tube alloys, and gives ASTM specifications and typical uses for each of the alloys.

Table 1 Copper tube alloys and typical applications

UNS No.	Alloy type	ASTM specifications	Type uses
C10200	Oxygen-free copper	B 68, B 75, B 88, B 111, B 188, B 280, B 359, B 372, B 395, B 447	Bus tube, conductors, wave guides
C12200	Phosphorus deoxidized copper	B 68, B 75, B 88, B 111, B 280, B 306, B 359, B 360, B 395, B 447, B 543	Water tubes; condenser, evaporator and heat-exchanger tubes; air conditioning and refrigeration, gas, heater and oil burner lines; plumbing pipe and steam tubes; brewery and distillery tubes; gasoline, hydraulic and oil lines; rotating heads
C19200	Copper	B 111, B 359, B 395, B 469	Automotive hydraulic brake lines; flexible hose
C23000	Red brass, 85%	B 111, B 135, B 359, B 395, B 543	Condenser and heat-exchanger tubes, flexible hose; plumbing pipe; pump lines
C26000	Cartridge brass, 70%	B 135	Plumbing brass goods

C33000	Low-leaded brass (tube)	B 135	Pump and power cylinders and liners; plumbing brass goods
C36000	Free-cutting brass	. . .	Screw machine parts; plumbing goods
C43500	Tin brass	. . .	Bourdon tubes; musical instruments
C44300, C4400, and C44500	Inhibited admiralty metal	B 111, B 359, B 395	Condenser, evaporator, and heat-exchanger tubes; distiller tubes
C 46400, C46500, C46600, and C46700	Naval brass	. . .	Marine hardware, nuts
C60800	Aluminum bronze, 5%	B 111, B 359, B 395	Condenser, evaporator and heat-exchanger tubes; distiller tubes
C65100	Silicon bronze B	B 315	Heat-exchanger tubes; electrical conduits
C65500	Silicon bronze A	B 315	Chemical equipment, heat-exchanger tubes; piston rings
C68700	Arsenical aluminum brass	B 111, B 359, B 395	Condenser, evaporator and heat-exchanger tubes; distiller tubes
C70600	Copper-nickel, 10%	B 111, B 359, B 395, B 466, B 467,B 543, B 552	Condenser, evaporator and heat-exchanger tubes; salt water piping; distiller tubes
C71500	Copper-nickel, 30%	B 111, B 359, B 395, B 446, B 467, B543, B552	Condenser, evaporator and heat-exchanger tubes; distiller tubes; salt water piping

Frequently, resistance to corrosion is a critical factor in selecting a tube alloy for a specific application. Information that can help determine the alloy(s) most suitable for a given type of service is found in the article "Corrosion Characteristics of Copper and Copper Alloys" in this Section.

Joints in copper tube and pipe are made in various ways. Permanent joints can be made by brazing or welding. Semipermanent joints are made most often by soldering, usually in conjunction with standard socket-type solder fittings, but threaded joints also can be considered semipermanent joints for pipe. Detachable joints are almost always some form of mechanical joint--flared joints, flange-and-gasket joints, and joints made using any of a wide variety of specially designed compression fittings are all common.

Properties of Tube. As with most wrought products, the mechanical properties of copper tube depend on prior processing. With copper, it is not so much the methods used to produce tube, but rather the resulting metallurgical condition that has the greatest bearing on properties. Table 2 summarizes tensile properties for selected tube alloys in their most widely used conditions.

Table 2 Typical mechanical properties for copper alloy tube

Temper	Tensile strength		Yield strength[a]		Elongation[b], %
	MPa	**ksi**	**MPa**	**ksi**	
C10200					
OS050	220	32	69	10	45
OS025	235	34	76	11	45
H55	275	40	220	32	25
H80	380	55	345	50	8
C12200					
OS050	220	32	69	10	45
OS025	235	34	76	11	45
H55	275	40	220	32	25
H80	380	55	345	50	8
C19200					
H55[c]	290	42	205[d]	30[d]	35
C23000					
OS050	275	40	83	12	55
OS015	305	44	125	18	45
H55	345	50	275	40	30
H80	485	70	400	58	8
C26000					

OS050	325	47	105	15	65
OS025	360	52	140	20	55
H80	540	78	440	64	8
C33000					
OS050	325	47	105	15	60
OS025	360	52	140	20	50
H80	515	75	415	60	7
C43500					
OS035	315	46	110	16	46
H80	515	75	415	60	10
C44300, C44400, C44500					
OS025	365	53	150	22	65
C46400, C46500, 46600, C46700[(e)]					
H80	605	88	455	66	18
C60800					
OS025	415	60	185	27	55
C65100					
OS015	310	45	140	20	55
H80	450	65	275	40	20
C65500					
OS050	395	57	. . .	. . .	70

H80	640	93	. . .	. . .	22
C68700					
OS025	415	60	185	27	55
C70600					
OS025	305	44	110	16	42
H55	415	60	395	57	10
C71500					
0S025	415	60	170	25	45

Tube size: 25 mm (1 in.) outside diameter by 1.65 mm (0.065 in.) wall.

(a) 0.5% extension under load.

(b) In 50 mm (2 in.).

(c) Tube size: 4.8 mm (0.1875 in.) outside diameter by 0.76 mm (0.030 in.) wall.

(d) 0.2% offset.

(e) Tube size: 9.5 mm (0.375 in.) outside diameter by 2.5 mm (0.097 in.) wall

Production of Tube Shells

Copper tubular products are typically produced from shells made by extruding or piercing copper billets.

Extrusion of copper and copper alloy tube shells is done by heating a billet of material above the recrystallization temperature, and then forcing material through an orifice in a die and over a mandrel held in position with the die orifice. The clearance between mandrel and die determines the wall thickness of the extruded tube shell.

In extrusion, the die is located at one end of the container section of an extrusion press; the metal to be extruded is driven through the die by a ram, which centers the container from the end opposite the die. Tube shells are produced either by starting with a hollow billet or by a two-step operation in which a solid billet is first pierced and then extruded.

Extrusion pressure varies with alloy composition. C36000 (61.5Cu-3Pb-35.5Zn) requires a relatively low pressure, whereas C26000 (70Cu-30Zn) and C44300 (71.5Cu-1Sn-27.5Zn-0.06As) require the highest pressure of all brasses. Most of the coppers require an extrusion pressure intermediate between those for C26000 and C36000. C71500 (70Cu-30Ni) requires a very high extrusion pressure.

Extrusion pressure also depends on billet temperature, extrusion ratio (the ratio of the cross-sectional area of the billet to that of the extruded section), speed of extrusion, and degree of lubrication. The flow of metal during extrusion depends on many factors, including copper content of the metal, amount of lubricant, and die design.

Rotary piercing on a Mannesmann mill is another method commonly used to produce seamless pipe and tube from copper and certain copper alloys. Piercing is the most severe forming operation customarily applied to metals. The process takes advantage of tensile stresses that develop the center of a billet when it is subjected to compressive forces around the periphery. In rotary piercing, one end of a heated cylindrical billet is fed between rotating work rolls that lie in a horizontal plane and are inclined at an angle to the axis of the billet (Fig. 1). Guide rolls beneath the billet prevent it from dropping from between the work rolls. Because the work rolls are set at an angle to each other as well as to the billet, the billet is simultaneously rotated and driven forward toward the piercing plug, which is held in position between the work rolls.

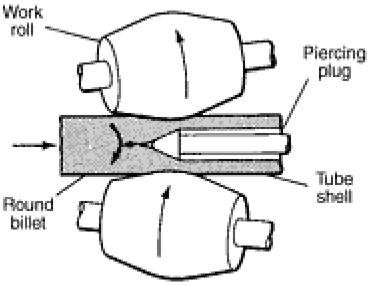


Fig. 1 Schematic diagram of metal piercing. Arrows indicate direction of motion.

The opening between work rolls is set smaller than the billet, and the resultant pressure acting around the periphery of the billet opens up tensile cracks, and then a rough hole, at the center of the billet just in front of the piercing plug. The piercing plug assists in further opening the axial hole in the center of the billet, smooths the wall of the hole, and controls the wall thickness of the formed tube.

Coppers and plain alpha brasses can be pierced, provided the lead content is held to <0.01%. Alpha-beta brasses can tolerate higher levels of lead without adversely affecting their ability to be pierced.

When piercing brass, close temperature control must be maintained because the range in which brass can be pierced is narrow. Each alloy has a characteristic temperature range within which it is sufficiently plastic for piercing to occur. Below this range, the central hole does not open up properly under the applied peripheral forces. Overheating can lead to cracked surfaces. Suggested piercing temperatures for various alloys are given in the following table:

UNS number	Piercing temperature	
	°C	**°F**
C11000	815-870	1500-1600
C12200	815-870	1500-1600
C22000	815-870	1500-1600

C23000	815-870	1500-1600
C26000	760-790	1400-1450
C28000	705-760	1300-1400
C46400	730-790	1350-1450

Production of Finished Tubes

Welded tube is made from clean strip in either cold-rolled or annealed tempers. The strip is formed into a tubular shape on a precision forming mill.

For forge-welded tube, the edges of the strip are heated to the required welding temperature, usually by high-frequency electric current, and are pressed firmly together causing a forge-type joint to be formed with internal and external flash or bead. The external flash is always removed, providing a smooth external surface. The internal flash is also removed by scarfing, providing a smooth, clean internal surface.

For fusion-welded tube, the edges of the strip are brought together and welded, usually by a gas tungsten arc welding process, without the addition of filler metal, causing a fusion-type joint to be formed with no internal or external flash or bead.

Welded tube can be used in the as-welded condition or, subsequent to welding, can be further processed by the standard cold drawing, reducing, and annealing processes.

Cold drawing of extruded or pierced tube shells to smaller sizes is done on draw blocks for coppers and on draw benches for brasses and other alloys. With either type of machine, the metal is cold worked by pulling the tube through a die that reduces the diameter. Concurrently, wall thickness is reduced by drawing over a plug or mandrel that can be either fixed or floating. Cold drawing increases the strength of the material and simultaneously reduces ductility. Tube size is reduced--outside diameter, inside diameter, wall thickness, and cross-sectional area all are smaller after drawing. Because the metal work hardens, tubes can be annealed at intermediate stages when drawing to small sizes. However, coppers are so ductile that they frequently can be drawn to finished size without intermediate annealing.

Tube reducing is an alternative process for cold sizing of the tube. In tube reducing, semicircular grooved dies are rolled or rocked back and forth along the tube while a tapered mandrel inside the tube controls the inside diameter and wall thickness. The process yields tube having very accurate dimensions and better concentricity than can be achieved by tube drawing.

The grooves in the tube-reducing dies are tapered, with one end of the grooved section being somewhat larger than the outside diameter of the tube to be sized. As the dies are rocked, the tube is pinched against the tapered mandrel, which reduces wall thickness and increases tube length. The tube is fed longitudinally, and rotated on its axis to distribute the cold work uniformly around the circumference. Feeding and rotating are synchronized with die motion and occur after the dies have completed their forward stroke.

Tube reducing can be used for all alloys that can be drawn on draw benches. Slight changes in die design and operating conditions may be required to accommodate different alloys. Small-diameter tube may be produced by block or bench drawing following tube reducing.

Product Specifications

Copper tube and pipe are available in a wide variety of nominal diameters and wall thicknesses, from small-diameter capillary tube to 300 mm (12 in.) nominal-diameter pipe. To a certain extent, dimensions and tolerances for copper tube and pipe depend on the type of service for which they are intended. The standard dimensions and tolerances for several kinds of copper tube and pipe are given in the ASTM specifications listed in Table 3, along with other requirements for the tubular products. Seamless copper tube for automotive applications ($\frac{1}{8}$ to $\frac{3}{4}$ in. in nominal diameter) is covered by SAE J528. Requirements for copper tube and pipe to be used in condensers, heat exchangers, economizers, and similar unfired pressure vessels are also given in the ASME specifications listed in Table 3. (ASME materials specifications are almost always identical to ASTM specifications having the same numerical designation; for example, ASME SB111 is identical to ASTM B 111.) Certain tube alloys are covered in AMS specifications, which apply to materials for aerospace applications. Typical examples include:

AMS specification	Product	Copper alloy
4555	Seamless brass tube, light annealed	C26000 C33000
4558	Seamless brass tube drawn	C33200
4625	Phosphor bronze, hard temper	C51000
4640	Aluminum bronze	C63000
4665	Seamless silicon bronze tube, annealed	C65500

Table 3 ASTM and ASME specifications for copper tube and pipe

Tubular product	ASTM	ASME
Seamless pipe and tube		
Seamless copper alloy (C69100) pipe and tube	B 706	. . .
Seamless pipe and tube, copper-nickel alloy[(a)]	B 466	SB466
	B466M[(a)]	
Seamless pipe and tube, copper-silicon alloy	B 315	SB315
Seamless pipe and tube, for electrical conductors	B 188	. . .
Seamless pipe, standard sizes	B42	SB42
Seamless red brass pipe, standard sizes	B 43	SB43

Seamless pipe, threadless	B 302	. . .
Seamless tube		
Seamless copper alloy tubes (C19200 and C70600), for pressure applications	B 469	. . .
Seamless copper-nickel tubes, for desalting plants	B 552	. . .
Seamless tube(a)	B 75	SB75
	B 75M(a)	. . .
Seamless tube, brass(a)	B 135	SB135
	B 135M(a)	. . .
Seamless tube, bright annealed(a)	B 68	. . .
	B 68M(a)	. . .
Seamless tube, capillary, hard drawn	B 360	. . .
Seamless tube, condenser and heat exchanger(a)	B 111, B 395	SB111, SB395
	B111M(a)	. . .
	B 395M(a)	. . .
Seamless tube, condenser and heat exchanger, with integral fins(a)	B 359	SB359
	B 359M(a)	. . .
Seamless tube, for air conditioning and refrigeration service	B280	. . .
Seamless tube, drainage	B 306	. . .
Seamless tube, general requirements(a)	B 251	. . .
	B 251M(a)	. . .
Seamless tube, rectangular waveguide	B372	. . .

Seamless tube, water(a)	B 88	. . .
	B 88M(a)	. . .
Welded pipe and tube		
Welded copper alloy pipe	B 608	SB467
Hard temper welded copper tube (C21000), for general plumbing and fluid conveyance	B 642	. . .
Welded brass tube, for general application	B 587	. . .
Welded copper tube, for air conditioning refrigeration	B 640	. . .
Welded pipe and tube, copper-nickel alloy	B 467	SB467
Welded tube, C10800 and 12000(a)	B 543	SB543
	B 543M(a)	. . .
Welded tube, all other coppers	B 447	. . .

(a) Suffix "M" indicates a metric specification.

Additional information about product specifications for copper tubular products can be found in the *Standards Handbook for Wrought and Cast Copper and Copper Alloys* (Part 6, Specifications Index), published by the Copper Development Association Inc.

Copper Wire and Cable

Introduction

WIRE made from copper and copper alloys has been used since about 2000 to 3000 B.C. According to archaeological evidence, the ancient Assyrians, Babylonians, and Egyptians were skilled in producing copper wire for ornamental purposes. Drawing wire through a die is a much more modern development. Development of wiredrawing processes during the Middle Ages concentrated to a large extent on drawing iron and steel wires to make pins and instrument strings. But with the invention of the electric telegraph in 1847 came the requirement for long continuous lengths of electric conductor wire made of copper. In 1850, copper wire was used to make a submarine cable connecting England and France.

At the beginning of the twentieth century, wire was still being drawn through single dies--a process commonly known as "bull-block" drawing. Dies were made by punching a series of holes in a steel plate.

Multiple wiredrawing machines were introduced around 1900. As a result, chilled cast iron plates and dies that could be reamed to size replaced the punch-sized, steel-plate dies. Lubricants were introduced because of the considerable heat generated by friction between the wire-and-draw capstan and by successive reductions through progressively smaller dies. In turn, use of lubricants permitted wire to be drawn at faster speeds.

The prime development during the 1920s was the introduction of drawing dies made of tungsten carbide. High hardness and lack of porosity make tungsten carbide dies ideal for high-speed wiredrawing. Tungsten carbide dies are standard today. For very fine wire sizes, below ~1.6 mm (0.064 in.), diamond dies are used.

Classification of Copper for Conductors

Copper metals used for electrical conductors fall into three general categories: high-conductivity coppers, high-copper alloys, and electrical bronzes.

High-conductivity coppers are covered by ASTM specifications B 4, B 5, B 170, B 442, and B 623. ASTM B 4 covers both high-resistance lake copper and low-resistance lake copper. Lake copper is fire refined from local Lake Superior ore deposits. ASTM B 5 covers copper electrolytically refined from blister copper, converter copper, black copper, or lake copper. ASTM B 170 covers oxygen-free electrical copper.

Some specialty coppers are produced by adding minimal amounts of hardening agents (such as chromium, tellurium, beryllium, cadmium, or zirconium). These are used in applications where high-anneal resistance is required.

A series of bronzes have been developed for use as conductors; these alloys are covered by ASTM B 105. These bronzes are intended to provide better corrosion resistance and higher tensile strengths than standard conductor coppers.

Classification of Wire and Cable

Round Wire. Standard nominal diameters and cross-sectional areas of solid round copper wires used as electrical conductors are prescribed in ASTM B 258. Wire sizes have almost always been designated in the American Wire Gauge (AWG) system. This system is based on fixed diameters for two wire sizes (4/0 and 36 AWG, respectively) with a geometric progression of wire diameters for the thirty-eight intermediate gages and for gages smaller than 36 AWG (see Table 1). This is an inverse series in which a high number denotes a smaller wire diameter. Each increase of one AWG number is approximately equivalent to a 20.7% reduction in cross-sectional area.

Table 1 Sizes of round wire in the American Wire Gauge (AWG) system and the properties of solid annealed copper wire (ASTM B 3)

Conductor size, AWG	Conductor diameter		Conductor area at 20 °C (68 °F)		Annealed copper (ASTM B 3)			
					Net weight[a]		**Elongation**[b], **%**	**Nominal resistance**[c], **Ω/1000 ft (305 m)**
	mm	**in.**	**mm^2**	**Circular mils**	**kg/km**	**lb/1000 ft**		
4/0	11.684	0.4600	107.0	211,600	953.2	640.5	35	0.0490
3/0	10.404	0.4096	85.0	167,800	755.7	507.8	35	0.06180
2/0	9.266	0.3648	67.4	133,100	599.4	402.8	35	0.07792
1/0	8.252	0.3249	53.5	105,600	475.5	319.5	35	0.09821
1	7.348	0.2893	42.4	83,690	377.0	253.3	30	0.1239

2	6.543	0.2576	33.6	66,360	299.0	200.9	30	0.1563
3	5.827	0.2294	26.7	52,620	237.1	159.3	30	0.1971
4	5.189	0.2043	21.2	41,740	188.0	126.3	30	0.2485
5	4.620	0.1819	16.8	33,090	149.1	100.2	30	0.3134
6	4.115	0.1620	13.3	26,240	118.2	79.44	30	0.3952
7	3.665	0.1443	10.5	20,820	93.8	63.03	30	0.4981
8	3.264	0.1285	8.37	16,510	74.4	49.98	30	0.6281
9	2.906	0.1144	6.63	13,090	59.0	39.62	30	0.7923
10	2.588	0.1019	5.26	10,380	46.8	31.43	25	0.9992
11	2.304	0.0907	4.17	8,230	37.1	24.9	25	1.26
12	2.052	0.0808	3.31	6,530	29.5	19.8	25	1.59
13	1.829	0.0720	2.63	5,180	23.4	15.7	25	2.00
14	1.628	0.0641	2.08	4,110	18.5	12.4	25	2.52
15	1.450	0.0571	1.65	3,260	14.7	9.87	25	3.18
16	1.290	0.0508	1.31	2,580	11.6	7.81	25	4.02
17	1.151	0.0453	1.04	2,050	9.24	6.21	25	5.06
18	1.024	0.0403	0.823	1,620	7.32	4.92	25	6.40
19	0.912	0.0359	0.654	1,290	5.80	3.90	25	8.04
20	0.813	0.0320	0.517	1,020	4.61	3.10	25	10.2
21	0.724	0.0285	0.411	812	3.66	2.46	25	12.8
22	0.643	0.0253	0.324	640	2.89	1.94	25	16.2

23	0.574	0.0226	0.259	511	2.31	1.55	25	20.3
24	0.511	0.0201	0.205	404	1.82	1.22	20	25.7
25	0.455	0.0179	0.162	320	1.44	0.970	20	32.4
26	0.404	0.0159	0.128	253	1.14	0.765	20	41.0
27	0.361	0.0142	0.102	202	0.908	0.610	20	51.4
28	0.320	0.0126	0.081	159	0.716	0.481	20	65.2
29	0.287	0.0113	0.065	128	0.576	0.387	20	81.0
30	0.254	0.0100	0.051	100	0.451	0.303	15	104.0
31	0.226	0.0089	0.040	79.2	0.357	0.240	15	131.0
32	0.203	0.0080	0.032	64.0	0.289	0.194	15	162.0
33	0.180	0.0071	0.026	50.4	0.228	0.153	15	206.0
34	0.160	0.0063	0.020	39.7	0.179	0.120	15	261.0
35	0.142	0.0056	0.016	31.4	0.141	0.0949	15	330.0
36	0.127	0.0050	0.013	25.0	0.113	0.0757	15	415.0
37	0.114	0.0045	0.010	20.2	0.0912	0.0613	15	513.0
38	0.102	0.0040	0.0081	16.0	0.0720	0.0484	15	648.0
39	0.089	0.0035	0.0062	12.2	0.0552	0.0371	15	850.0
40	0.079	0.0031	0.0049	9.61	0.0433	0.0291	15	1,079.0
41	0.071	0.0028	0.0040	7.84	0.0353	0.0237	15(d)	1,323.0
42	0.0635	0.0025	0.0032	6.25	0.0281	0.0189	15(d)	1,659.0
43	0.056	0.0022	0.0023	4.48	0.0219	0.0147	15(d)	2,143.0

44	0.050	0.0020	0.0020	4.00	0.0180	0.0121	15(d)	2,593.0
45	0.045	0.00176	0.0016	3.10	0.0140	0.00938	(d)	3,345.6
46	0.040	0.00157	0.00125	2.46	0.0111	0.00745	(d)	4,216.0
47	0.036	0.00140	0.00099	1.96	0.00882	0.00593	(d)	5,291.6
48	0.031	0.00124	0.00078	1.54	0.00673	0.00466	(d)	6,734.7
49	0.028	0.00111	0.00062	1.23	0.00554	0.00372	(d)	8,432.1
50	0.025	0.00099	0.00050	0.980	0.00442	0.00297	(d)	10,583
51	0.022	0.00088	0.00039	0.774	0.00348	0.00234	(d)	13,400
52	0.020	0.00078	0.00031	0.608	0.00274	0.00184	(d)	17,058
53	0.018	0.00070	0.00025	0.490	0.00220	0.00148	(d)	21,166
54	0.016	0.00062	0.00019	0.384	0.00173	0.00116	(d)	27,009
55	0.014	0.00055	0.00015	0.302	0.00136	0.000914	(d)	34,342
56	0.012	0.00049	0.0012	0.240	0.00108	0.000726	(d)	43,214

(a) Based on a density of 8.89 g/cm^3 at 20 °C (68 °F).

(b) Minimum elongation in 250 mm (10 in.).

(c) Based on a resistivity value of 0.017241 Ω· mm^2/m (875 · 20 Ω· lb/mile^2), which is the resistivity for the International Annealed Copper Standard (IACS) of electrical conductivity.

(d) Elongation not specified in ASTM B 3

Hard-drawn copper wire and hard-drawn copper alloy wire for electrical purposes are specified in ASTM B 1 and B 105, respectively. ASTM B 3 specifies soft (or annealed) copper wire. Tables 1 and 2 give the sizes and properties of wire specified in ASTM B 1, B 3, and B 105.

Table 2 Tensile properties of hard-drawn copper and copper alloy round wire

Conductor size, AWG	Hard-drawn copper wire (ASTM B 1)					Minimum tensile strength of hard-drawn copper alloy wire (ASTM B 105)												ASTM B 105 minimum elongation, %
	Nominal tensile strength[(a)]		**Nominal elongation[(b)], %**	**Nominal breaking strength**		**C65100**		**C51000**		**C50700**		**C16500**		**C19600**		**C16200**		
	MPa	**ksi**		**N**	**lbf**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	
4/0	340	49.0	3.8	36,220	8,143	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
3/0	350	51.0	3.3	29,900	6,720	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
2/0	365	52.8	2.8	24,550	5,519	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1/0	375	54.5	2.4	20,095	4,518	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
1	385	56.1	2.2	17,290	3,888	672	97.5	707	102.5	510	74.0	524	76.0	510	74.0	496	72.0	2.2
2	395	57.6	2.0	13,350	3,002	716	103.8	750	108.8	552	80.0	536	77.8	520	75.5	507	73.5	2.0
3	405	59	1.8	10,850	2,439	741	107.5	776	112.5	586	85.0	547	79.3	534	77.5	517	75.0	1.8
4	415	60.1	1.7	8,762	1,970	760	110.2	794	115.2	614	89.0	558	80.9	545	79.0	527	76.4	1.6
5	420	61.2	1.6	7,072	1,590	774	112.2	808	117.2	638	92.5	568	82.4	552	80.0	534	77.5	1.5
6	430	62.1	1.4	5,693	1,280	786	114.0	820	119.0	654	94.8	579	84.0	558	81.0	542	78.6	1.4

7	435	63	1.3	4,580	1,030	795	115.3	829	120.3	665	96.5	590	85.5	568	82.4	550	79.8	1.3
8	440	63.7	1.3	3,674	826.1	804	116.6	836	121.6	675	97.9	600	87.0	576	83.5	558	81.0	1.3
9	445	64.3	1.2	2,940	660.9	812	117.8	847	122.8	683	99.0	610	88.5	583	84.6	567	82.2	1.2
10	445	64.9	1.2	2,354	529.3	820	118.9	854	123.9	690	100.1	620	90.0	590	85.5	575	83.4	1.2
11	450	65.4	1.1	1,880	423	826	119.8	860	124.8	698	101.2	630	91.3	597	86.6	583	84.6	1.2
12	455	65.7	1.1	1,500	337	832	120.6	866	125.6	705	102.2	638	92.6	605	87.7	591	85.7	1.1
13	455	65.9	1.1	1,190	268	836	121.2	870	126.2	710	103.0	647	93.8	612	88.8	598	86.8	1.1
14	455	66.2	1.0	952	214	839	121.7	874	126.7	715	103.7	655	95.0	619	89.8	605	87.8	1.1
15	460	66.4	1.0	756	170	843	122.2	877	127.2	720	104.4	662	96.0	625	90.6	612	88.7	1.0
16	460	66.6	1.0	600	135	845	122.5	879	127.5	725	105.2	669	97.0	634	92.0	617	89.5	1.0
17	460	66.8	1.0	480	108	847	122.8	881	127.8	730	105.9	676	98.0	640	92.8	623	90.3	1.0
18	460	67.0	1.0	380	85.5	848	123.0	883	128.0	735	106.6	680	98.6	645	93.5	627	91.0	0.9
19	463	67.2	. . .	302	68.0	849	123.2	884	128.2	740	107.3	683	99.0	648	94.0	632	91.6	0.9
20	465	67.4	. . .	241	54.2	852	123.5	886	128.5	745	108.0	686	99.5	652	94.5	636	92.2	0.9

21	467	67.7	. . .	192	43.2	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
22	468	67.9	. . .	152	34.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
23	470	68.1	. . .	121	27.3	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
24	471	68.3	. . .	96.5	21.7	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
25	473	68.6	. . .	77.0	17.3	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
26	474	68.8	. . .	60.9	13.7	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
27	476	69.0	. . .	48.5	10.9	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
28	478	69.3	. . .	38.4	8.64	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
29	479	69.4	. . .	31.0	6.96	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
30	481	69.7	. . .	24.3	5.47	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
31	482	69.9	. . .	19.3	4.35	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
32	484	70.2	. . .	15.7	3.53	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
33	485	70.4	. . .	12.4	2.79	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
34	487	70.6	. . .	9.79	2.20	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

35	489	70.9	. . .	7.78	1.75	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
36	490	71.1	. . .	6.23	1.40	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
37	492	71.3	. . .	5.03	1.13	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
38	493	71.5	. . .	4.39	0.898	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
39	495	71.8	. . .	3.07	0.691	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
40-44	496	72.0	. . .	2.42-1.00	0.543-0.226	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

(a) Tensile strengths cannot always be met if wire is drawn into coils of less than 480 mm (19 in.).

(b) Elongation in 250 mm (10 in.)

Square and Rectangular Wire. ASTM B 48 specifies soft (annealed) square and rectangular copper wire.

Stranded wire is normally used in electrical applications where some degree of flexing is encountered either in service or during installation. In order of increasing flexibility, the common forms of stranded wire are concentric lay, unilay, rope lay, and bunched.

Concentric-lay stranded wire and cable are composed of a central wire surrounded by one or more layers of helically laid wires, with the direction of lay reversed in successive layers, and with the length of lay increased for each successive layer. The outer layer usually has a left-hand lay.

ASTM B 8 establishes five classes of concentric-lay stranded wire and cable, from AA (the coarsest) to D (the finest). Table 3 gives details of concentric-lay constructions.

Table 3 Characteristics of concentric-lay stranded copper conductors specified in ASTM B 8

Conductor size, circular mills or AWG	Nominal weight, lb/1000 ft(a)	Nominal resistance, Ω/1000 ft(a)	Class AA		Class A		Class B		Class C		Class D	
			Number of wires	**Diameter of individual wires, mils(a)**	**Number of wires**	**Diameter of individual wires, mils(a)**	**Number of wires**	**Diameter of individual wires, mils(a)**	**Number of wires**	**Diameter of individual wires, mils(a)**	**Number of wires**	**Diameter of individual wires, mils(a)**
5,000,000	15,890	0.002178	. . .	. . .	169	172.0	217	151.8	271	135.8	271	135.8
4,500,000	14,300	0.002420	. . .	. . .	169	163.2	217	144.0	271	128.9	271	128.9
4,000,000	12,590	0.002696	. . .	. . .	169	153.8	217	135.8	271	121.5	271	121.5
3,500,000	11,020	0.003082	. . .	. . .	127	166.0	169	143.9	217	127.0	271	113.6
3,000,000	9,353	0.003561	. . .	. . .	127	153.7	169	133.2	217	117.6	271	105.2
2,500,000	7,794	0.004278	. . .	. . .	91	165.7	127	140.3	169	121.6	217	107.3
2,000,000	6,175	0.005289	. . .	. . .	91	148.2	127	125.5	169	108.8	217	96.0
1,900,000	5,886	0.005568	. . .	. . .	91	144.5	127	122.3	169	106.0	217	93.6
1,800,000	5,558	0.005 877	. . .	. . .	91	140.6	127	119.1	169	103.2	217	91.1
1,750,000	6,403	0.006223	. . .	. . .	91	138.7	127	117.4	169	101.8	217	89.8
1,700,000	5,249	0.006045	. . .	. . .	91	136.7	127	115.7	169	100.3	217	88.5

1,600,000	4,940	0.006612	. . .	. . .	91	132.6	127	112.2	169	97.3	217	85.9
1,500,000	4,631	0.007052	. . .	. . .	61	156.6	91	128.4	127	108.7	169	94.2
1,400,000	4,323	0.007556	. . .	. . .	61	151.5	91	124.0	127	105.0	169	91.0
1,300,000	4,014	0.008137	. . .	. . .	61	146.0	91	119.5	127	101.2	169	87.7
1,250,000	3,859	0.008463	. . .	. . .	61	143.1	91	117.2	127	99.2	169	86.0
1,200,000	3,705	0.008815	. . .	. . .	61	140.3	91	114.8	127	97.2	169	84.3
1,100,000	3,396	0.009617	. . .	. . .	61	134.3	91	109.9	127	93.1	169	80.7
1,000,000	3,088	0.010 88	37	164.4	61	128.0	61	128.0	91	104.8	127	88.7
900,000	2,779	0.01175	37	156.0	61	121.5	61	121.5	91	99.4	127	84.2
800,000	2,470	0.01322	37	147.0	61	114.5	61	114.5	91	93.8	127	79.4
750,000	2,316	0.01410	37	142.4	61	110.9	61	110.9	91	90.8	127	76.8
700,000	2,161	0.01511	37	137.5	61	107.1	61	107.1	91	87.7	127	74.2
650,000	2,007	0.01627	37	132.5	61	103.2	61	103.2	91	84.5	127	71.5
600,000	1,853	0.01763	37	127.3	37	127.3	61	99.2	91	81.2	127	68.7

550,000	1,698	0.01923	37	121.9	37	121.9	61	95.0	91	77.7	127	65.8
500,000	1,544	0.02116	19	162.2	37	116.2	37	116.2	61	90.5	91	74.1
450,000	1,389	0.02351	19	153.9	37	110.3	37	110.3	61	85.9	91	70.3
400,000	1,235	0.02645	19	145.1	19	145.1	37	104.0	61	81.0	91	66.3
350,000	1,081	0.03022	12	170.8	19	135.7	37	97.3	61	75.7	91	62.0
300,000	926.3	0.03526	12	158.1	19	125.7	37	90.0	61	70.1	91	57.4
250,000	771.9	0.04231	12	144.3	19	114.6	37	82.2	61	64.0	91	52.4
4/0	655.3	0.04999	7	173.9	7	173.9	19	105.5	37	75.6	61	58.9
3/0	518.1	0.06304	7	154.8	7	154.8	19	94.0	37	67.3	61	52.4
2/0	410.9	0.07948	7	137.9	7	137.9	19	83.7	37	60.0	61	46.7
1/0	326.0	0.1002	7	122.8	7	122.8	19	74.5	37	53.4	. . .	. . .
1	258.4	0.1264	3	167.0	7	109.3	19	66.4	37	47.6	. . .	. . .
2	204.9	0.1594	3	148.7	7	97.4	7	57.4	19	59.1	. . .	. . .
3	162.5	0.2010	3	132.5	7	86.7	7	86.7	19	52.6	. . .	. . .

4	128.9	0.2534	3	118.0	7	77.2	7	77.2	19	48.9	. . .	. . .
5	102.2	0.3197	. . .	. . .	. . .	. . .	7	68.8	19	41.7	. . .	. . .
6	81.05	0.4031	. . .	. . .	. . .	. . .	7	61.2	19	37.2	. . .	. . .
7	64.28	0.5081	. . .	. . .	. . .	. . .	7	54.5	19	33.1	. . .	. . .
8	50.98	0.6407	. . .	. . .	. . .	. . .	7	48.6	19	29.5	. . .	. . .
9	40.42	0.8081	. . .	. . .	. . .	. . .	7	43.2	19	28.2	. . .	. . .

Nominal resistance is for uncoated wire.

(a) Units used in ASTM B 8 specification

Unilay stranded wire is composed of a central core surrounded by more than one layer of helically laid wires, all layers having a common lay length and direction. This type of wire sometimes is referred to as "smooth bunch". The layers usually have a left-hand lay.

Rope-lay stranded wire and cable are composed of a stranded member (or members) as a central core, around which are laid one or more helical layers of similar stranded members. The members can be concentric or bunch stranded. ASTM B 173 and B 172 establish five classes of rope-lay stranded conductors: classes G and H, which have concentric members and classes I, K, and M, which have bunched members. Tables 4 and 5 show construction details. These cables are normally used to make large, flexible conductors for portable service, such as mining cable or apparatus cable.

Table 4 Characteristics of rope-lay stranded copper conductors having uncoated or tinned concentric members specified in ASTM B 173

Conductor sizes, circular mils or AWG	Class G				Class H			
	Diameter of individual wires, mils[(a)]	**Number of ropes**	**Number of wires each rope**	**Net weight, lb/1000 ft**[(a)]	**Diameter of individual wires, mils**[(a)]	**Number of ropes**	**Number of wires each rope**	**Net weight, lb/1000 ft**[(a)]
5,000,000	65.7	61	19	16,052	53.8	91	19	15,057
4,500,000	62.3	61	19	14,434	51.0	91	19	14,429
4,000,000	58.7	61	19	12,814	48.1	91	19	12,835
3,500,000	55.0	61	19	11,249	45.0	91	19	11,234
3,000,000	50.9	61	19	9,635	41.7	91	19	9,647
2,500,000	59.6	37	19	8,012	46.4	61	19	8,006
2,000,000	53.3	37	19	6,408	41.5	61	19	6,405
1,900,000	52.0	37	19	6,099	40.5	61	19	6,100
1,800,000	50.6	37	19	5,775	39.4	61	19	5,773
1,750,000	49.9	37	19	5,617	38.9	61	19	5,627
1,700,000	49.2	37	19	5,460	38.3	61	19	5,455
1,600,000	47.7	37	19	5,132	37.2	61	19	5,146
1,500,000	59.3	61	7	4,772	46.2	37	19	4,815
1,400,000	57.3	61	7	4,456	44.6	37	19	4,487

1,300,000	55.2	61	7	4,135	43.0	37	19	4,171
1,250,000	54.1	61	7	3,972	42.2	37	19	4,017
1,200,000	53.0	61	7	3,814	41.3	37	19	3,847
1,100,000	50.8	61	7	3,502	39.6	37	19	3,537
1,000,000	48.4	61	7	3,179	37.7	37	19	3,206
900,000	45.9	61	7	2,859	35.8	37	19	2,891
800,000	43.3	61	7	2,544	33.7	37	19	2,562
750,000	41.9	61	7	2,383	32.7	37	19	2,412
700,000	40.5	61	7	2,226	31.6	37	19	2,252
650,000	39.0	61	7	2,046	30.4	37	19	2,085
600,000	37.5	61	7	1,908	29.2	37	19	1,923
550,000	35.9	61	7	1,749	28.0	37	19	1,768
500,000	43.9	37	7	1,579	34.2	61	7	1,587
450,000	41.7	37	7	1,425	32.5	61	7	1,433
400,000	39.3	37	7	1,265	30.6	61	7	1,271
350,000	36.8	37	7	1,109	28.6	61	7	1,110
300,000	34.0	37	7	947.1	26.5	61	7	953.0
250,000	31.1	37	7	792.4	24.2	61	7	794.8
4/0	39.9	19	7	666.6	28.6	37	7	670.1
3/0	35.5	19	7	527.7	25.5	37	7	532.7
2/0	31.6	19	7	418.1	22.7	37	7	422.3

1/0	28.2	19	7	333.0	20.7	37	7	334.3
1	25.1	19	7	263.8	18.0	37	7	265.4
2	36.8	7	7	206.9	22.3	19	7	208.2
3	37.8	7	7	164.4	19.9	19	7	165.8
4	29.2	7	7	130.3	17.7	19	7	131.2
5	26.0	7	7	103.3	15.8	19	7	104.5
6	23.1	7	7	81.52	14.0	19	7	82.06
7	20.6	7	7	64.83	12.5	19	7	65.42
8	18.4	7	7	51.72	11.1	19	7	51.59
9	15.3	7	7	40.59	9.9	19	7	41.04
10	14.6	7	7	32.57	. . .	. . .	. . .	. . .
12	11.5	7	7	20.20	. . .	. . .	. . .	. . .
14	9.2	7	7	12.93	. . .	. . .	. . .	. . .

(a) Units used in ASTM B 173

Table 5 Characteristics of rope-lay stranded copper conductors having uncoated or tinned bunched members specified in ASTM B 172

Conductor size, circular mils or AWG	Class of strand	Construction and wire size, AWG	Total number of wires	Approximate diameter, in.	Net weight, lb/1000 ft
1,000,000	I	19 × 7 × 19/24	2,527	1.290	3306
	K	37 × 7 × 39/30	10,101	1.329	3272
	M	61 × 7 × 59/34	25,193	1.353	3239
900,000	I	19 × 7 × 17/24	2,261	1.217	2959

	K	37 × 7 × 35/30	9,065	1.255	2936
	M	61 × 7 × 53/34	22,631	1.279	2909
800,000	I	19 × 7 × 15/24	1,995	1.140	2611
	K	19 × 7 × 60/30	7,980	1.174	2585
	M	61 × 7 × 47/34	20,069	1.200	2580
750,000	I	19 × 7 × 14/24	1,862	1.099	2437
	K	19 × 7 × 57/30	7,581	1.143	2455
	M	61 × 7 × 44/34	18,788	1.160	2415
700,000	I	19 × 7 × 13/24	1,729	1.057	2262
	K	19 × 7 × 52/30	6,916	1.089	2240
	M	61 × 7 × 41/34	17,507	1.117	2251
650,000	I	19 × 7 × 12/24	1,596	1.014	2088
	K	19 × 7 × 49/30	6,517	1.056	2111
	M	61 × 7 × 38/34	16,226	1.074	2086
600,000	I	7 × 7 × 30/24	1,470	0.971	1906
	K	19 × 7 × 45/30	5,985	1.010	1938
	M	61 × 7 × 35/34	14,945	1.028	1921
550,000	I	7 × 7 × 28/24	1,372	0.936	1779
	K	19 × 7 × 41/30	5,453	0.961	1766
	M	61 × 7 × 32/34	13,664	0.981	1757
500,000	I	7 × 7 × 25/24	1,225	0.882	1588

	K	19 × 7 × 38/30	5,054	0.924	1637
	M	37 × 7 × 49/34	12,691	0.900	1631
450,000	I	7 × 7 × 23/24	1,127	0.845	1461
	K	19 × 7 × 34/30	4,522	0.871	1465
	M	37 × 7 × 44/34	11,396	0.892	1465
400,000	I	7 × 7 × 20/24	980	0.785	1270
	K	19 × 7 × 30/30	3,990	0.816	1292
	M	37 × 7 × 39/34	10,101	0.837	1298
350,000	I	7 × 7 × 18/24	882	0.743	1143
	K	19 × 7 × 26/30	3,458	0.757	1120
	M	37 × 7 × 34/34	8,806	0.779	1132
300,000	I	7 × 7 × 15/24	735	0.675	953
	K	7 × 7 × 61/30	2,989	0.701	959
	M	19 × 7 × 57/34	7,581	0.720	975
250,000	I	7 × 7 × 13/24	637	0.626	826
	K	7 × 7 × 61/30	2,499	0.638	802
	M	19 × 7 × 48/34	6,384	0.658	821
4/0	I	19 × 28/24	532	0.569	683
	K	7 × 7 × 43/30	2,107	0.584	676
	M	19 × 7 × 40/34	5,320	0.598	684
3/0	I	19 × 22/24	418	0.502	537

	K	7 × 7 × 34/30	1,666	0.516	535
	M	19 × 7 × 32/34	4,256	0.532	547
2/0	I	19 × 18/24	342	0.452	439
	K	7 × 7 × 27/30	1,323	0.457	424
	M	19 × 7 × 25/34	3,325	0.467	427
1/0	I	19 × 14/24	266	0.396	342
	K	19 × 56/30	1,064	0.408	338
	M	7 × 7 × 54/34	2,646	0.414	337
1	I	7 × 30/24	210	0.350	267
	K	19 × 44/30	836	0.359	266
	M	7 × 7 × 43/34	2,107	0.368	268
2	I	7 × 23/24	161	0.304	205
	K	19 × 35/30	665	0.319	211
	M	7 × 7 × 34/34	1,666	0.325	212
3	I	7 × 19/24	133	0.275	169
	K	19 × 28/30	532	0.283	169
	M	7 × 7 × 27/34	1,323	0.288	168
4	I	7 × 15/24	105	0.243	134
	K	7 × 60/30	420	0.250	132
	M	19 × 56/34	1,064	0.257	134
5	I	7 × 12/24	84	0.216	107

	K	7 × 48/30	336	0.223	106
	M	19 × 44/34	836	0.226	105
6	I	7 × 9/24	63	0.186	80
	K	7 × 38/30	266	0.197	84
	M	19 × 35/34	665	0.201	84
7	K	7 × 30/30	210	0.174	66
	M	19 × 28/34	532	0.178	67
8	K	7 × /30	168	0.155	53
	M	7 × 60/34	420	0.158	53
9	K	7 × 19/30	133	0.137	42
	M	7 × 48/34	336	0.140	42
10	M	7 × 37/34	259	0.122	33
12	M	7 × 24/34	168	0.097	21

Bunch stranded wire is composed of any number of wires twisted together in the same direction without regard to geometric arrangement of the individual strands. ASTM B 174 provides for five classes (I, J, K, L, and M); these conductors are commonly used in flexible cords, hookup wires, and special flexible welding conductors. Table 6 gives typical construction details.

Table 6 Characteristics of bunch stranded copper conductors having uncoated or tinned members specified in ASTM B 174

Conductor size, AWG	Class of strand	No. and size of wire, AWG	Approximate diameter, in.	Approximate weight, lb/1000 ft
7	I	52/24	0.168	64.9
8	I	41/24	0.148	51.1
9	I	33/24	0.132	41.2

10	I	26/24	0.117	32.4
	J	65/28	0.118	31.9
	K	104/30	0.120	32.1
12	J	41/28	0.093	20.1
	K	65/30	0.094	20.1
	L	104/32	0.096	20.6
14	J	26/28	0.073	12.7
	K	41/30	0.074	12.7
	L	65/32	0.075	12.8
	M	104/34	0.076	12.7
16	J	16/28	0.057	7.84
	K	26/30	0.058	8.03
	L	41/32	0.059	8.10
	M	65/34	0.059	7.97
18	J	10/28	0.044	4.90
	K	16/30	0.045	4.94
	L	26/32	0.046	5.14
	M	41/34	0.046	5.02
20	J	7/28	0.038	3.43
	K	10/30	0.035	3.09
	L	16/32	0.036	3.16

	M	26/34	0.037	3.19

Tin-Coated Wire. Solid and stranded wires are available with tin coatings. These are manufactured to the latest revisions of ASTM B 33, which covers soft or annealed tinned-copper wires, and B 246, which covers hard-drawn or medium-hard-drawn tinned-copper wires. Table 7 gives characteristics of tinned, round, solid wire.

Table 7 Characteristics of tinned solid round copper wire specified in ASTM B 33, B 246, and B 258

Conductor size, AWG	Net weight, lb/1000 ft	Soft (annealed) wire		Hard-drawn wire	
		Nominal resistance, Ω/1000 ft	**Minimum elongation[(a)], %**	**Nominal resistance, Ω/1000 ft**	**Minimum breaking strength, lbf**
2	200.9	0.1609	25	. . .	. . .
3	159.3	0.2028	25	. . .	. . .
4	126.3	0.2557	25	0.2680	1773
5	100.2	0.3226	25	0.3380	1432
6	79.44	0.4067	25	0.4263	1152
7	63.03	0.5127	25	0.5372	927.3
8	49.98	0.6465	25	0.6776	743.1
9	39.62	0.8154	25	0.8545	595.1
10	31.43	1.039	20	1.087	476.1
11	24.9	1.31	20	1.37	381.0
12	19.8	1.65	20	1.73	303.0
13	15.7	2.08	20	2.18	241.0
14	12.4	2.62	20	2.74	192.0
15	9.87	3.31	20	3.46	153.0
16	7.81	4.18	20	4.37	121.0

17	6.21	5.26	20	. . .	. . .
18	4.92	6.66	20	. . .	. . .
19	3.90	8.36	20	. . .	. . .
20	3.10	10.6	20	. . .	. . .
21	2.46	13.3	20	. . .	. . .
22	1.94	16.9	20	. . .	. . .
23	1.55	21.1	20	. . .	. . .
24	1.22	26.7	15	. . .	. . .
25	0.970	34.4	15	. . .	. . .
26	0.765	43.5	15	. . .	. . .
27	0.610	54.5	15	. . .	. . .
28	0.481	69.3	15	. . .	. . .
29	0.387	86.1	15	. . .	. . .
30	0.303	110.0	10	. . .	. . .
31	0.204	141.0	10	. . .	. . .
32	0.194	174.0	10	. . .	. . .
33	0.153	221.0	10	. . .	. . .
34	0.120	281.0	10	. . .	. . .

(a) In 250 mm (10 in.)

Fabrication of Wire Rod

Wire rod is the intermediate product in the manufacture of wire. Although wire rod is the term used in the U.S. for the intermediate product, the term drawing stock is used in international standards and customs documents.

Rolling. The traditional process for converting prime copper into wire rod involves hot rolling of cast wirebar. Almost all drawing stock is rolled to 8 mm (0.32 in.) diameter. Larger sizes, up to 22 mm (0.87 in.) or more in diameter, are available on special order.

Some special oxygen-free copper wirebar is produced by vertical casting, but most wirebar is produced by horizontal casting of tough-pitch copper into open molds. The oxygen content is controlled at 0.03 to 0.06% to give a level surface. Cast wirebars weigh ~110 to 135 kg (250 to 300 lb) each. The ends are tapered to facilitate entry into the first pass of the hot rolling mill.

Prior to rolling, bars are heated to ~925 °C (1700 °F) in a neutral atmosphere and then rolled on a continuous mill through a series of reductions to yield round rod ~6 to 22 mm ($\frac{1}{4}$ to $\frac{7}{8}$ in.) in diameter. The hot-rolled rod is coiled, water quenched, and then pickled to remove the black cupric oxide that forms during rolling. This method can produce rod at rates up to 7.5 kg/s (30 tons/h).

Disadvantages of this process include:

- High capital investment to achieve low operating cost
- Relatively small coils that must be welded together for efficient production, where the welded junctions present potential sources of weakness in subsequent wiredrawing operations
- Unsuitability of rod rolled from cast wirebars for certain specialized wire applications

Continuous Casting. Because of the disadvantages inherent in producing rolled rod from conventionally cast wirebars, processes have been developed for continuously converting liquid metal directly into wire rod, thus avoiding the intermediate wirebar stage. Continuously cast wire rod has come to dominate the copper wire rod market and now accounts for more than 50% of the total amount of wire rod produced.

Advantages of continuous casting and rolling include:

- Large coil weights, up to 10 Mg (11 tons)
- Ability to reprocess scrap at considerable savings
- Improved rod quality and surface condition
- Homogeneous metallurgical conditions and close process control
- Low capital investment and low operating costs for moderate production rates

Wiredrawing and Wire Stranding

Preparation of Rod. In order to provide a wire of good surface quality, it is necessary to have a clean wire rod with a smooth, oxide-free surface. Conventional hot-rolled rod must be cleaned in a separate operation, but with the advent of continuous casting, which provides better surface quality, a separate cleaning operation is not required. Instead, the rod passes through a cleaning station as it exits from the rolling mill.

The standard method for cleaning copper wire rod is pickling in hot 20% sulfuric acid followed by rinsing in water. When fine wire is being produced, it is necessary to provide rod of even better surface quality. This can be achieved in a number of ways. One method is open-flame annealing of cold-drawn rod--that is, heating to 700 °C (1300 °F) in an oxidizing atmosphere. This eliminates shallow discontinuities. A more common practice, especially for fine magnet-wire applications, is die shaving, where rod is drawn through a circular cutting die made of steel or carbide to remove approximately 0.13 mm (0.005 in.) from the entire surface of the rod. A further refinement of this cleaning operation for rod made from conventionally cast wirebar involves scalping the top surface of cast wirebar and subsequently die shaving the hot-rolled bar.

Wiredrawing. Single-die machines called bull blocks are used for drawing special heavy sections such as trolley wire. Drawing speeds range from ~1 to 2.5 m/s (200 to 500 ft/min). Tallow is generally used as the lubricant, and the wire is drawn through hardened steel or tungsten carbide dies. In some instances, multiple-draft tandem bull blocks (in sets of 3 or 5 passes) are used instead of single-draft machines.

Tandem drawing machines having 10 to 12 dies for each machine are used for break-down of hot-rolled or continuous-cast copper rod. The rod is reduced in diameter from 8.3 mm (0.325 in.) to ~2 mm (0.08 in.) by drawing it through dies at speeds up to 25 m/s (5000 ft/min). The drawing machine operates continuously; the operate merely welds the end of each rod coil to the start of the next coil.

Intermediate and fine wires are drawn on smaller machines that have 12 to 20 or more dies each. The wire is reduced in steps of 20 to 25% in cross-sectional area. Intermediate machines can produce wire as small as 0.5 mm (0.020 in.) in diameter, and fine wire machines can produce wire in diameters from 0.5 mm (0.020 in.) to less than 0.25 mm (0.010 in.). Drawing speeds are typically 25 to 30 m/s (5000 to 6000 ft/min) and may be even higher.

All drawing is performed with a copious supply of lubricant to cool the wire and prevent rapid die wear. Traditional lubricants are soap and fat emulsions, which are fed to all machines from a central reservoir. Breakdown of rod usually requires a lubricant concentration of ~7%, drawing of intermediate and fine wires, and concentrations of 2 to 3%. Today, synthetic lubricants are becoming more widely accepted.

Drawn wire is collected on reels or stem packs, depending on the next operation. Fine wire is collected on reels carrying as little as 4.5 kg (10 lb); large-diameter wire, on stem packs carrying up to 450 kg (1000 lb). To ensure continuous operation, many drawing machines are equipped with dual take-up systems. When one reel is filled, the machine automatically flips the wire onto an adjacent empty reel and simultaneously cuts the wire. This permits the operator to unload the full reel and replace it with an empty one without stopping the wiredrawing operation.

Production of Flat or Rectangular Wire. Depending on size and quantity, flat or rectangular wire is drawn on bull block machines or Turk's head machines, or is rolled on tandem rolling mills with horizontal and vertical rolls. Larger quantities are produced by rolling and smaller quantities are produced by drawing.

Annealing. Wiredrawing, like any other cold-working operation, increases tensile strength and reduces ductility of copper. Although it is possible to cold work copper up to 99% reduction in area, copper wire usually is annealed after 90% reduction.

In some plants, electrical-resistance heating methods are used to fully anneal copper wire as it exits from the drawing machines. Wire coming directly from drawing passes over suitably spaced contact pulleys that carry the electrical current necessary to heat the wire above the recrystallization temperature in less than a second.

In plants where batch annealing is practiced, drawn wire is treated either in a continuous tunnel furnace, where reels travel through a neutral or slightly reducing atmosphere and are annealed during transit, or in batch bell furnaces under a similar protective atmosphere. Annealing temperatures range from 400 to 600 °C (750 to 1100 °F) depending chiefly on wire diameter and reel weight.

Wire Coating. Four basic coatings are used on copper conductors for electrical applications:

- Lead, or lead alloy (80Pb-20Sn), ASTM B 189
- Nickel, ASTM B 355
- Silver, ASTM B 298
- Tin, ASTM B 33

Coatings are applied to:

- Retain solderability for hookup-wire applications
- Provide a barrier between the copper and insulation materials, such as rubber, that would react with the copper and adhere to it (thus making it difficult to strip insulation from the wire to make an electrical connection)
- Prevent oxidation of the copper during high-temperature service

Tin-lead alloy coatings and pure tin coatings are the most common; nickel and silver are used for specialty and high-temperature applications.

Copper wire can be coated by hot dipping in a molten metal bath, electroplating, or cladding. With the advent of continuous processes, electroplating has become the dominant process, especially because it can be completed "on line" following the wiredrawing operation.

Stranded wire is produced by twisting or braiding several wires together to provide a flexible cable. Different degrees of flexibility for a given current-carrying capacity can be achieved by varying the number, size, and arrangement of individual wires. Solid wire, concentric strand, rope strand, and bunched strand provide increasing degrees of flexibility; within the last three categories, a larger number of finer wires provides greater flexibility.

Stranded copper wire and cable are made on machines known as bunchers or stranders. Conventional bunchers are used for stranding small-diameter wires (34 AWG up to 10 AWG). Individual wires are payed off reels located alongside the equipment and are fed over flyer arms that rotate around the take-up reel to twist the wires. The rotational speed of the arm relative to the take-up speed controls the length of lay in the bunch. For small, portable, flexible cables, individual wires are usually 30 to 34 AWG, and there can be as many as 150 wires in each cable.

A tubular buncher has up to 18 wire-payoff reels mounted inside the unit. Wire is taken off each reel while it remains in a horizontal plane, is threaded along a tubular barrel, and is twisted together with other wires by a rotating action of the barrel. At the take-up end, the strand passes through a closing die to form the final bunch configuration. The finished strand is wound onto a reel that also remains within the machine.

Supply reels in conventional stranders for large-diameter wire are fixed onto a rotating frame within the equipment and revolve around the axis of the finished conductor. There are two basic types of machines. In one, known as a rigid frame strander, individual supply reels are mounted in such a way that each wire receives a full twist for every revolution of the strander. In the other, known as a planetary strander, the wire receives no twist as the frame rotates.

These types of stranders are comprised of multiple bays, with the first bay carrying six reels and subsequent bays carrying increasing multiples of six. The core wire in the center of the strand is payed off externally. It passes through the machine center and individual wires are laid over it. In this manner, strands with up to 127 wires are produced in one or two passes through the machine, depending on the capacity for stranding individual wires.

Normally, hard-drawn copper is stranded on a planetary machine so that the strand will not be as springy and will tend to stay bunched rather than spring open when it is cut off. The finished product is wound onto a power-driven external reel that maintains a prescribed amount of tension on the stranded wire.

Insulation and Jacketing

Of the three broad categories of insulation--polymeric, enamel, and paper-and-oil--polymeric insulation is the most widely used.

Polymeric Insulation. The most common polymers are polyvinyl chloride (PVC), polyethylene, ethylene propylene rubber (EPR), silicon rubber, polytetrafluoroethylene (PTFE), and fluorinated ethylene propylene (FEP). Polyimide coatings are used where fire resistance is of prime importance, such as in wiring harnesses for manned space vehicles. Until a few years ago, natural rubber was used, but this has now been supplanted by synthetics such as butyl rubber and EPR. Synthetic rubbers are used wherever good flexibility must be maintained, such as in welding or mining cable.

Many varieties of PVC are made, including several that are flame resistant. PVC has good dielectric strength and flexibility, and is one of the least expensive conventional insulating and jacketing materials, It is used mainly for communication wire, and low-voltage power cables. PVC insulation is normally selected for applications requiring continuous operation at temperatures up to 75 °C (165 °F).

Polyethylene, because of low and stable dielectric constant, is specified when better electrical properties are required. It resists abrasion and solvents. It is used chiefly for hookup wire, communication wire, and high-voltage cable. Cross-linked polyethylene (XLPE), which is made by adding organic peroxides to polyethylene and then vulcanizing the mixture, yields better heat resistance, better mechanical properties, better aging characteristics, and freedom from environmental stress cracking. Special compounding can provide flame resistance in cross-linked polyethylene. Typical uses include building wire, control cables, and power cables. The usual maximum sustained operating temperature is 90 °C (200 °F).

Polytetrafluoroethylene and fluorinated ethylene propylene are used to insulate jet aircraft wire, electronic equipment wire, and specialty control cables, where heat resistance, solvent resistance, and high reliability are important. These electrical cables can operate at temperatures up to 250 °C (480 °F).

All of the polymeric compounds are applied over copper conductors by hot extrusion. The extruders are machines that convert pellets or powders of thermoplastic polymers into continuous covers. The insulating compound is loaded into a hopper that feeds into a long, heated chamber. A continuously revolving screw moves the pellets into the hot zone where the polymer softens and becomes fluid. At the end of the chamber, molten compound is forced out through a small die over the moving conductor, which also passes through the die opening. As the insulated conductor leaves the extruder it is water cooled and taken up on reels. Cables jacketed with EPR and XLPE go through a vulcanizing chamber prior to cooling to complete the cross-linking process.

Enamel Film Insulation. Film-coated wire, usually fine magnet wire, is composed of a metallic conductor coated with a thin, flexible enamel film. These insulated conductors are used for electromagnetic coils in electrical devices and must be capable of withstanding high breakdown voltages. Temperature ratings range from 105 to 220 °C (220 to 425 °F), depending on enamel composition. The most commonly used enamels are based on polyvinyl acetals, polyesters, and epoxy resins.

Equipment for enamel coating of wire is often custom built, but standard lines are available. Basically, systems are designed to insulate large numbers of wire simultaneously. Wires are passed through an enamel applicator that deposits a controlled thickness of liquid enamel onto the wire. Then the wire travels through a series of ovens to cure the coating, and finished wire is collected on spools. In order to build up a heavy coating of enamel, it may be necessary to pass wires through the system several times. In recent years, some manufacturers have experimented with powder-coating methods. These avoid evolution of solvents, which is characteristic of curing conventional enamels, and thus make it easier for the manufacturer to meet Occupational Safety and Health Administration and Environmental Protection Agency standards. Electrostatic sprayers, fluidized beds, and other experimental devices are used to apply the coatings.

Paper-and-Oil Insulation. Cellulose is one of the oldest materials for electrical insulation and is still used for certain applications. Oil-impregnated cellulose paper is used to insulate high-voltage cables for critical power-distribution applications. The paper, which can be applied in tape form, is wound helically around the conductors using special machines in which six to twelve paper-filled pads are held in a cage that rotates around the cable. Paper layers are wrapped alternately in opposite directions, free of twist. Paper-wrapped cables then are placed inside special impregnating tanks to fill the pores in the paper with oil and to ensure that all air has been expelled from the wrapped cable.

The other major use of paper insulation is for flat magnet wire. In this application, magnet-wire strip (with a width-to-thickness ratio greater than 50 to 1) is helically wrapped with one or more layers of overlapping tapes. These may be bonded to the conductor with adhesives or varnishes. The insulation provides highly reliable mechanical separation under conditions of electrical overload.

Copper Alloy Castings

Introduction

COPPER ALLOY CASTINGS are used in applications that require superior corrosion resistance, high thermal or electrical conductivity, good bearing surface qualities, or other special properties. Casting makes it possible to produce parts with shapes that cannot be easily obtained by fabrication methods such as forming or machining. Often, it is more economical to produce a part as a casting than to fabricate it by other means.

Types of Copper Alloys

Because pure copper is extremely difficult to cast and is prone to surface cracking, porosity problems, and the formation of internal cavities, small amounts of alloying elements (such as beryllium, silicon, nickel, tin, zinc, and chromium) are used to improve the casting characteristics of copper. Larger amounts of alloying elements are added for property improvement.

As described in the "Introduction and Overview" article in this Section, the copper-base castings are designated by the united number system (UNS) with numbers ranging from C80000 to C99999. Also, copper alloys in the cast form are sometimes classified according to their freezing range (that is, the temperature range between the liquidus and solidus temperatures). The freezing range of various copper alloys is discussed in the subsection "Control of Solidification" in this article.

Compositions of copper casting alloys differ from those of their wrought counterparts for various reasons. Generally, casting permits greater latitude in the use of alloying elements, because the effects of composition on hot or cold working properties are not important. However, imbalances among certain elements, and trace amounts of certain impurities in some alloys, will diminish castability and can result in castings of questionable quality.

Many of the casting alloys have lead contents of 5% or more. Alloys containing such high percentages of lead are not suited to hot working, but are ideal for low- to medium-speed bearings, where the lead prevents galling and excessive wear under boundary-lubrication conditions.

The tolerance for impurities is normally greater in castings than in their wrought counterparts--again because of the adverse effects certain impurities have on hot or cold workability. On the other hand, impurities that inhibit response to heat treatment must be avoided in both castings and wrought products. The choice of an alloy for any casting usually depends on five factors: metal cost, castability, machinability, properties, and final cost.

Castability

Castability should not be confused with fluidity, which is only a measure of the distance to which a metal will flow before solidifying. Fluidity is thus one factor determining the ability of a molten alloy to completely fill a mold cavity in every detail. Castability, on the other hand, is a general term relating to the ability to reproduce fine detail on a surface. Colloquially, good castability refers to the case with which an alloy responds to ordinary foundry practice without requiring special techniques for gating, risering, melting, sand conditioning, or any of the other factors involved in making good castings. High fluidity often ensures good castability, but it is not solely responsible for that quality in a casting alloy.

Foundry alloys generally are classified as high-shrinkage or low-shrinkage alloys. The former class includes the manganese bronzes, aluminum bronzes, silicon bronzes, silicon brasses, and some nickel silvers. They are more fluid than the low-shrinkage red brasses, more easily poured, and give high-grade castings in the sand, permanent mold, plaster, die, and centrifugal casting processes. With high-shrinkage alloys, careful design is necessary to promote directional solidification, avoid abrupt changes in cross section, avoid notches (by using generous fillets), and properly place gates and risers; all of these design precautions help avoid internal shrinks and cracks. Turbulent pouring must be avoided to prevent the formation of dross becoming entrapped in the casting. Liberal use of risers or exothermic compounds ensures adequate molten metal to feed all sections of the casting. Table 1 presents foundry characteristics of selected standard alloys, including a comparative ranking of both fluidity and overall castability for sand casting; number 1 represents the highest castability or fluidity ranking.

Table 1 Foundry properties of the principal copper alloys for sand casting

UNS No.	Common name	Shrinkage allowance, %	Approximate liquidus temperature		Castability rating(a)	Fluidity rating(a)
			°C	**°C**		
C83600	Leaded red brass	5.7	1010	1850	2	6
C84400	Leaded semired brass	2.0	980	1795	2	6

C84800	Leaded semired brass	1.4	955	1750	2	6
C85400	Leaded yellow brass	1.5-1.8	940	1725	4	3
C85800	Yellow brass	2.0	925	1700	4	3
C86300	Manganese bronze	2.3	920	1690	5	2
C86500	Manganese bronze	1.9	880	1615	4	2
C87200	Silicon bronze	1.8-2.0	. . .	. . .	5	3
C87500	Silicon brass	1.9	915	1680	4	1
C90300	Tin bronze	1.5-1.8	980	1795	3	6
C92200	Leaded tin bronze	1.5	990	1810	3	6
C93700	High-lead tin bronze	2.0	930	1705	2	6
C94300	High-lead tin bronze	1.5	925	1700	6	7
C95300	Aluminum bronze	1.6	1045	1910	8	3
C95800	Aluminum bronze	1.6	1060	1940	8	3
C97600	Nickel-silver	2.0	1145	2090	8	7
C97800	Nickel-silver	1.6	1180	2160	8	7

(a) Relative rating for casting in sand molds. The alloys are ranked from 1 to 8 in both overall castability and fluidity; 1 is the highest or best possible rating.

All copper alloys can be successfully cast in sand. Sand casting allows the greatest flexibility in casting size and shape and is the most economical casting method if only a few castings are made (die casting is more economical above ∼ 50,000 units). Permanent mold casting is best suited for tin, silicon, aluminum, and manganese bronzes, and yellow brasses. Die casting is well suited for yellow brasses, but increasing amounts of permanent mold alloys are also being die cast. Size is a definite limitation for both methods, although large slabs weighing as much as 4500 kg (10,000 lb) have been cast in permanent molds. Brass die castings generally weigh less than 0.2 kg (0.5 lb) and seldom exceed 0.9 kg (2 lb). The limitation of size is due to the reduced die life with larger castings.

Virtually all copper alloys can be cast successfully by the centrifugal casting process. Castings of almost every size from less than 100 g to more than 22,000 kg (<0.25 to >50,000 lb) have been made.

Because of their low lead contents, aluminum bronzes, yellow brasses, manganese bronzes, low-nickel bronzes, and silicon brasses and bronzes are best adapted to plaster mold casting. For most of these alloys, lead should be held to a minimum because it reacts with the calcium sulfate in the plaster, resulting in discoloration of the surface of the casting and increased cleaning and machining costs. Size is a limitation on plaster mold casting, although aluminum bronze castings that weigh as little as 100 g (0.25 lb) have been made by the investment (lost-wax) process, and castings that weigh more than 150 kg (330 lb) have been made by conventional plaster molding.

Control of Solidification. Production of consistently sound castings requires an understanding of the solidification characteristics of the alloys as well as knowledge of relative magnitudes of shrinkage. The actual amount of contraction during solidification does not differ greatly from alloy to alloy. The distribution, however, is a function of the freezing range and the temperature gradient in critical sections. Manganese and aluminum bronzes are similar to steel in that their freezing ranges are quite narrow--about 40 and 14 °C (70 and 25 °F), respectively. Large castings can be made by the same conventional methods used for steel, as long as proper attention is given to placement of gates and risers--both those for controlling directional solidification and those for feeding the primary central shrinkage cavity.

Tin bronzes have wider freezing ranges (~165 °C or 300 °F for C83600). Alloys with such wide freezing ranges form a mushy zone during solidification, resulting in interdendritic shrinkage or microshrinkage. Because feeding cannot occur properly under these conditions, porosity results in the affected sections. In overcoming this effect, design and riser placement, plus the use of chills, are important. Another means of overcoming interdendritic shrinkage is to maintain close temperature control of the metal during pouring and to provide for rapid solidification. These requirements limit section thickness and pouring temperatures, and this practice requires a gating system that will ensure directional solidification. Sections up to 25 mm (1 in.) in thickness are routinely cast. Sections up to 50 mm (2 in.) thick can be cast, but only with difficulty and under carefully controlled conditions. A bronze with a narrow solidification (freezing) range and good directional solidification characteristics is recommended for castings having section thicknesses greater than about 25 mm (1 in.).

It is difficult to achieve directional solidification in complex castings. The most effective and most easily used device is the chill. For irregular sections, chills must be shaped to fit the contour of the section of the mold in which they are placed. Insulating pads and riser sleeves sometimes are effective in slowing down the solidification rate in certain areas to maintain directional solidification.

Mechanical Properties

Most copper-base casting alloys containing tin, lead, or zinc have only moderate tensile and yield strengths, low-to-medium hardness, and high elongation. When higher tensile or yield strength is required, the aluminum bronzes, manganese bronzes, silicon brasses, silicon bronzes, beryllium coppers, and some nickel-silvers are used instead. Most of the higher-strength alloys have better-than-average resistance to corrosion and wear. Table 2 presents mechanical and physical properties of copper-base casting alloys. (Throughout this discussion, as well as in Table 2, the mechanical properties quoted are for sand cast test bars. Properties of the castings themselves may be lower, depending on section size and process-design variables.)

Table 2 Typical properties of copper casting alloys

UNS No.	Tensile strength		Yield strength[(a)]		Compressive yield strength[(b)]		Elongation, %	Hardness, HB[(c)]	Electrical conductivity, %IACS
	MPa	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**			
ASTM B 22									
C86300	820	119	468	68	490	71	18	225[(d)]	8.0
C90500	317	46	152	22	. . .	. . .	30	75	10.9

C91100	241	35	172	25	125 min	18 min	2	135[(d)]	8.5
C91300	241	35	207	30	165 min	24 min	0.5	170[(d)]	7.0
ASTM B 61									
C92200	280	41	110	16	105	15	45	64	14.3
ASTM B 62									
C83600	240	35	105	15	100	14	32	62	15.0
ASTM B 66									
C93800	221	32	110	16	83	12	20	58	11.6
C94300	186	27	90	13	76	11	15	48	9.0
C94400	221	32	110	16	. . .	. . .	18	55	10.0
C94500	172	25	83	12	. . .	. . .	12	50	10.0
ASTM B 67									
C94100	138	20	97	14	. . .	. . .	15	44	. . .
ASTM B 148									
C95200	552	80	200	29	207	30	38	120[(d)]	12.2
C95300	517	75	186	27	138	20	25	140[(d)]	15.3
C95400	620	90	255	37	. . .	. . .	17	170[(d)]	13.0
C95400 (HT)[(e)]	758	110	317	46	. . .	. . .	15	195[(d)]	12.4
C95410	620	90	255	37	. . .	. . .	17	170[(d)]	13.0
C95410 (HT)[(e)]	793	116	400	58	. . .	. . .	12	225[(d)]	10.2
C95500	703	102	303	44	. . .	. . .	12	200[(d)]	8.8

C95500 (HT)(e)	848	123	545	79	. . .	. . .	5	248(d)	8.4
C95600	517	75	234	34	. . .	. . .	18	140(d)	8.5
C95700	655	95	310	45	. . .	. . .	26	180(d)	3.1
C95800	662	96	255	37	241	35	25	160(d)	7.0
ASTM B 176									
C85700	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
C85800	380	55	205(f)	30(f)	. . .	. . .	15	. . .	22.0
C86500	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
C87800	620	90	205(f)	30(f)	. . .	. . .	25	. . .	6.5
C87900	400	58	205(f)	30(f)	. . .	. . .	15	. . .	. . .
C99700	415	60	180	26	. . .	. . .	15	120(d)	3.0
C99750	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
ASTM B 584									
C83450	255	37	103	15	69	10	34	62	20.0
C83600	241	35	103	15	97	14	32	62	15.1
C83800	241	35	110	16	83	12	28	60	15.3
C84400	234	34	97	14	. . .	. . .	28	55	16.8
C84800	262	38	103	15	90	13	37	59	16.4
C85200	262	38	90	13	62	9	40	46	18.6
C85400	234	34	83	12	62	9	37	53	19.6
C85700	352	51	124	18	. . .	. . .	43	76	21.8

C86200	662	96	331	48	352	51	20	180(d)	7.4
C86300	820	119	469	68	489	71	18	225(d)	8.0
C86400	448	65	166	24	159	23	20	108(d)	19.3
C86500	489	71	179	26	166	24	40	130(d)	20.5
C86700	586	85	290	42	. . .	. . .	20	155(d)	16.7
C87300	400	58	172	25	131	19	35	85	6.1
C87400	379	55	165	24	. . .	. . .	30	70	6.7
C87500	469	68	207	30	179	26	17	115	6.1
C87600	456	66	221	32	. . .	. . .	20	135(d)	8.0
C87610	400	58	172	25	131	19	35	85	6.1
C90300	310	45	138	20	90	13	30	70	12.4
C90500	317	46	152	22	103	15	30	75	10.9
C92200	283	41	110	16	103	15	45	64	14.3
C92300	290	42	138	20	69	10	32	70	12.3
C92600	303	44	138	20	83	12	30	72	10.0
C93200	262	38	117	17	. . .	. . .	30	67	12.4
C93500	221	32	110	16	. . .	. . .	20	60	15.0
C93700	269	39	124	18	124	18	30	67	10.1
C93800	221	32	110	16	83	12	20	58	11.6
C94300	186	27	90	13	76	11	15	48	9.0
C94700	345	50	159	23	. . .	. . .	35	85	11.5

C94700 (HT)(g)	620	90	483	70	. . .	. . .	10	210(d)	14.8
C94800	310	45	159	23	. . .	. . .	35	80	12.0
C94900	262 min	38 min	97 min	14 min	. . .	. . .	15 min	. . .	. . .
C96800	862 min	125 min	689 min(f)	100 min(f)	. . .	. . .	3 min	. . .	. . .
C97300	248	36	117	17	. . .	. . .	25	60	5.9
C97600	324	47	179	26	159	23	22	85	4.8
C97800	379	55	214	31	. . .	. . .	16	130(d)	4.5

Note: HT indicates alloy in heat-treated condition.

(a) At 0.5% extension under load.

(b) At a permanent set of 0.025 mm (0.001 in.).

(c) 500 kgf (1100 lbf) load.

(d) 3000 kgf (6600 lbf load).

(e) Heat treated at 900 °C (1650 °F), water quenched, tempered at 590 °C (1100 °F), and water quenched.

(f) At 0.2% offset.

(g) Solution anneal of 760 °C (1400 °F) for 4 h, water quench, and then aged at 315 °C (600 °F) for 5 h and air cooled.

Tensile strengths for cast test bars of aluminum bronzes and manganese bronzes range from 450 to 900 MPa (65 to 130 ksi), depending on composition; some aluminum bronzes attain maximum tensile strength only after heat treatment.

Although manganese and aluminum bronzes are often used for the same applications, the manganese bronzes are handled more easily in the foundry. As-cast tensile strengths as high as 800 MPa (115 ksi) and elongations of 15 to 20% can be obtained readily in sand castings; slightly higher values are possible in centrifugal castings. Stresses can be relieved at 175 to 200 °C (350 to 400 °F). Lead can be added to the lower-strength manganese bronzes to increase machinability, but at the expense of tensile strength and elongation. Lead content should not exceed 0.1% in high-strength manganese bronzes. Although manganese bronzes range in hardness from 125 to 250 HB, they are readily machined.

Tin is added to low-strength manganese bronzes to enhance resistance to dezincification, but it should be limited to 0.1% in high-strength manganese bronzes unless sacrifices in strength and ductility can be accepted.

Manganese bronzes are specified for marine propellers and fittings, pinions, ball bearing races, worm wheels, gear shift forks, and architectural work. Manganese bronzes are also used for rolling mill screw-down nuts and slippers, bridge trunnions, gears, and bearings, all of which require high strength and hardness.

Various cast aluminum bronzes contain 9 to 14% Al and lesser amounts of iron, manganese, or nickel. They have a very narrow solidification range; therefore, they have a greater need for adequate gating and risering than do most other copper casting alloys and thus are more difficult to cast. A wide range of properties can be obtained with these alloys, especially after heat treatment, but close control of composition is necessary. Like the manganese bronzes, aluminum bronzes can develop tensile strengths well over 700 MPa (100 ksi).

Most aluminum bronzes contain from 0.75 to 4% Fe to refine grain structure and increase strength. Alloys containing from 8 to 9.5% Al cannot be heat treated unless other elements (such as nickel or manganese) in amounts over 2% are added. They have higher tensile strengths and greater ductility and toughness than any of the ordinary tin bronzes. Applications include valve nuts, cam bearings, impellers, hangers in pickling baths, agitators, crane gears, and connecting rods.

The heat-treatable aluminum bronzes contain from 9.5 to 11.5% Al; they also contain iron, with or without nickel or manganese. These castings are quenched in water or oil from temperatures between 760 and 925 °C (1400 and 1700 °F) and tempered at 425 to 650 °C (800 to 1200 °F), depending on the exact composition and the required properties.

From the range of properties shown in Table 2, it can be seen that all the maximum properties cannot be obtained in any one aluminum bronze. In general, alloys with higher tensile strengths, yield strengths, and hardnesses have lower values of elongation. Typical applications of the higher-hardness alloys are rolling mill screw-down nuts and slippers, worm gears, bushings, slides, impellers, nonsparking tools, valves, and dies.

Aluminum bronzes resist corrosion in many substances, including pickling solutions. When corrosion occurs, it often proceeds by preferential attack of the aluminum-rich bronzes. Duplex alpha-plus-beta aluminum bronzes are more susceptible to preferential attack of the aluminum-rich phases than are the all-alpha aluminum bronzes.

Aluminum bronzes have fatigue limits that are considerably greater than those of manganese bronze or any other cast copper alloy. Unlike Cu-Zn and Cu-Sn-Pb-Zn alloys, the mechanical properties of aluminum and manganese bronzes do not decrease with increases in casting cross section. This is because these alloys have narrow freezing ranges, which result in denser structures when castings are properly designed and properly fed.

Whereas manganese bronzes experience hot shortness above 230 °C (450 °F), aluminum bronzes can be used at temperatures as high as 400 °C (750 °F) for short periods of time without an appreciable loss in strength. For example, a room-temperature tensile strength of 540 MPa (78 ksi) declines to 529 MPa (76.7 ksi) at 260 °C (500 °F), 460 MPa (67 ksi) at 400 °C (750 °F), and 400 MPa (58 ksi) at 540 °C (1000 °F). Corresponding elongation values change from 28% to 32, 35, and 25%, respectively.

Unlike manganese bronzes, many aluminum bronzes increase in yield strength and hardness but decrease in tensile strength and elongation upon slow cooling in the mold. Whereas some manganese bronzes precipitate a relatively soft phase during slow cooling, aluminum bronzes precipitate a hard constituent rather rapidly within the narrow temperature range of 565 to 480 °C (1050 to 900 °F). Therefore, large castings, or smaller castings that are cooled slowly, will have properties different from those of small castings cooled relatively rapidly. The same phenomenon occurs upon heat treating the hardenable aluminum bronzes. Cooling slowly through the critical temperature range after quenching, or tempering at temperatures within this range, will decrease elongation. An addition of 2 to 5% Ni greatly diminishes this effect.

Nickel brasses, silicon brasses, and silicon bronzes, although generally high in strength than red metal alloys, are used more for their corrosion resistance.

Cast beryllium coppers achieve variations in properties principally by varying heat treatment conditions. The "red" beryllium copper alloys are exemplified by C82000 and C82200; the "gold" alloys include C82400, C82500, C82600, and C82800. The casting alloys typically contain large amounts of beryllium than their wrought counterparts. The "gold" casting alloys, in particular, have excellent casting characteristics and can be poured at relatively low temperatures into molds with intricate shapes and fine detail.

Figure 1 shows distributions of hardness and tensile-strength data for separately cast test bars of three different alloys.

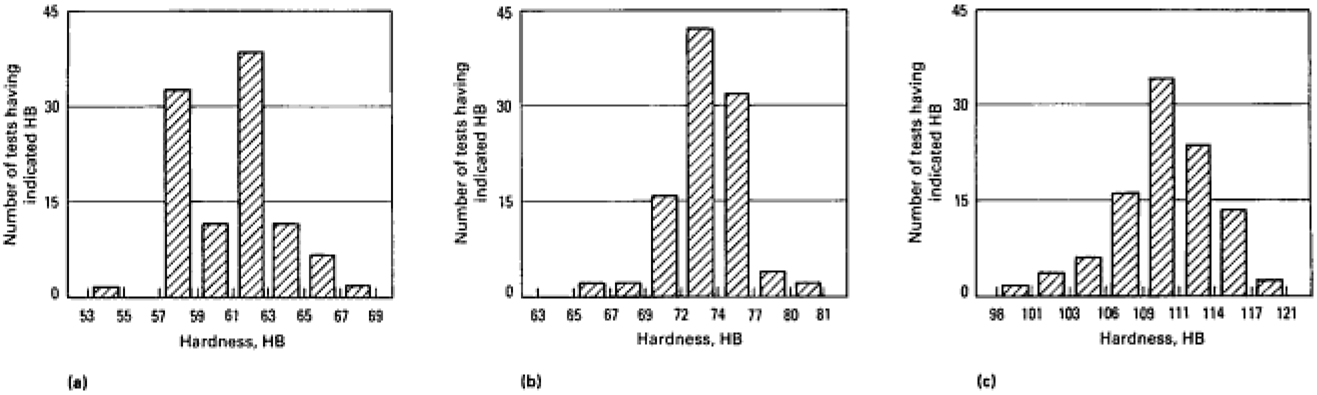


Fig. 1 Distribution of hardness over 100 tests for three copper casting alloys of different tensile strengths. (a) C83600. Tensile strength, 235 to 260 MPa (34 to 38 ksi); 500 kg (1100 lbf) load. (b) C90300. Tensile strength, 275 to 325 MPa (40 to 47 ksi); 500 kg (1100 lbf) load. (c) C87500. Tensile strength, 420 to 500 MPa (61 to 72 ksi); 1500 kg (3300 lbf) load

Properties of Test Bars. The mechanical properties of separately cast test bars often differ widely from those of production castings poured at the same time, particularly when the thickness of the casting differs markedly from that of the test bar.

The mechanical properties of tin bronzes are particularly affected by variations in casting section size. With increasing section sizes up to $\sim$50 mm (2 in.), the mechanical properties--both strength and elongation--of the casting themselves are progressively lower than the corresponding properties of separately cast test bars. Elongation is particularly affected; for some tin bronzes, elongation of a 50 mm (2 in.) section may be as little as $\frac{1}{10}$ that of a 10 mm (0.4 in.) section or of a separately cast test bar.

The metallurgical behavior of many copper alloy systems is complex. The cooling rate (a function of casting section size) directly influences grain size, segregation, and interdendritic shrinkage; these factors, in turn, affect the mechanical properties of the cast metal. Therefore, molding and casting techniques are based on metallurgical characteristics as well as on casting shape.

Dimensional Tolerances

Typical dimensional tolerances are different for castings produced by different molding methods. A molding process involving two or more mold parts requires greater tolerances for dimensions that cross the parting line than for dimensions wholly within one mold part. For castings made in green sand molds, tolerances across the parting line depend on the accuracy of pins and bushings that align the cope with the drag.

Figure 2 shows variations in two important dimensions for 50 production castings of red brass. The larger dimension presented the greatest difficulty; none of the 50 production castings had an actual dimension as large as the nominal design value. Figure 3 shows dimensional variations in two similar cored valve castings. For each design, both the cores and the corresponding cavities in the castings were measured for approximately 100 castings. For both designs, the castings had actual dimensions less than those of the cores. This indicates that cores may need to have a slightly larger nominal size than is desired in the finished casting in order to ensure proper as-cast hole sizes.

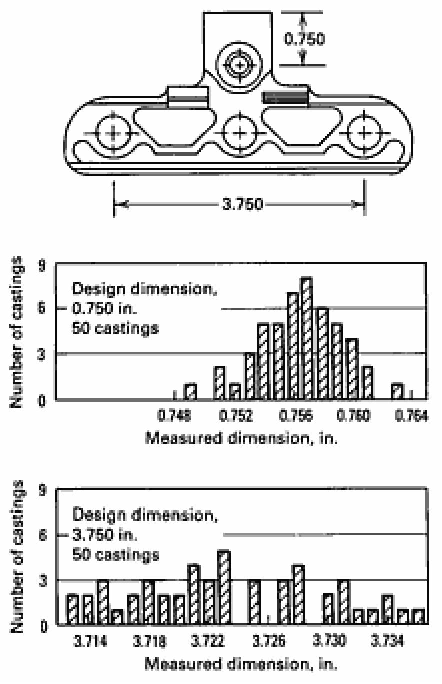


Fig. 2 Variations from design dimensions for a typical red brass casting. Parts were cast in green sand molds made using the same pattern. All dimensions are given in inches.

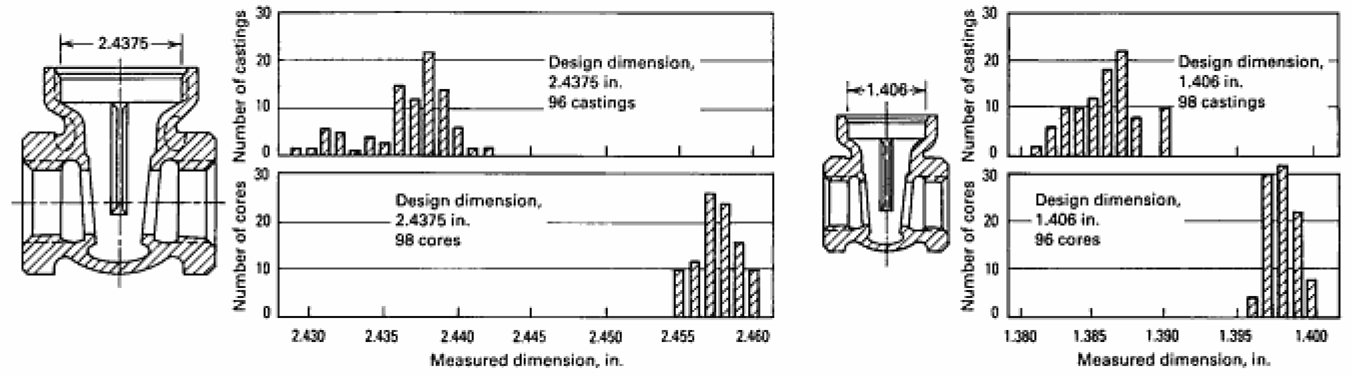


Fig. 3 Variations from design dimensions for two typical cast red brass valve bodies. Valve bodies, similar in design but of different sizes, were made using dry sand cores to shape the internal cavities. The upper histograms indicate dimensional variations for the castings; the lower histograms indicate variations for the corresponding cores. All dimensions are given in inches.

Machinability

Machinability ratings of copper casting alloys are similar to those of their wrought counterparts. The cast alloys can be separated into three groups. Table 3 shows the relative machinability of alloys belonging to the three groups.

Table 3 Machinability ratings of several copper casting alloys

UNS No.	Common name	Machinability rating, %[(a)]

Group 1: free-cutting alloys		
C83600	Leaded red brass	90
C83800	Leaded red brass	90
C84400	Leaded semired brass	90
C84800	Leaded semired brass	90
C94300	High-lead tin bronze	90
C85200	Leaded yellow brass	80
C85400	Leaded yellow brass	80
C93700	High-lead tin bronze	80
C93800	High-lead tin bronze	80
C93200	High-lead tin bronze	70
C93500	High-lead tin bronze	70
C97300	Leaded nickel brass	70
Group 2: moderately machinable alloys		
C86400	Leaded high-strength manganese bronze	60
C92200	Leaded tin bronze	60
C92300	Leaded tin bronze	60
C90300	Tin bronze	50
C90500	Tin bronze	50
C95600	Silicon-aluminum bronze	50
C95300	Aluminum bronze	35

C86500	High-strength manganese bronze	30
C82500	Beryllium copper	30
Group 3: hard-to-machine alloys		
C86300	High-strength manganese bronze	20
C95200	9% aluminum bronze	20
C95400	11% aluminum bronze	20
C95500	Nickel-aluminum bronze	20

(a) Expressed as a percentage of the machinability of C36000, free-cutting brass. The rating is based on relative speed for equivalent tool life. For example, a material having a rating of 50 should be machined at about half the speed that would be used to make a similar cut in C36000.

The first group includes only those containing a single copper-rich phase plus lead. Whether present merely to improve machinability or for some other purpose, lead facilitates chip breakage, thus allowing higher machining speeds with decreased tool wear and improved surface finishes.

Alloys of the second group contain two or more phases. Generally, the secondary phases are harder or more brittle than the matrix. Silicon bronzes, several aluminum bronzes, and the high-tin bronzes belong to this group. Hard and brittle secondary phases act as internal chip breakers, resulting in short chips and easier machining. Manganese bronzes produce a long spiral chip that is smooth on both sides and that does not break. Some aluminum bronzes, on the other hand, produce a long spiral chip that is smooth on both sides and that does not break. Some aluminum bronzes, on the other hand, produce a long spiral chip that is rough on the underside and that breaks, thus acting like a short chip. Some of the alloys in the second group are classified as moderately machinable because tools wear more rapidly when these alloys are machined, even though chip formation is entirely adequate.

The third group, the most difficult to machine, is composed mainly of the high-strength manganese bronzes and aluminum bronzes that are high in iron or nickel content.

General Purpose Alloys

General-purpose copper casting alloys are often classified as either red or yellow alloys. Table 2 show general properties of these alloys.

The leaded red and leaded semired brasses respond readily to ordinary foundry practice and are rated very high in castability. Alloy C83600 is the best known of this group and usually is referred to by a common name--85-5-5-5 or ounce metal. Alloy C83600 and the modification, C83800 (83-4-6-7), constitute the largest tonnage of copper-base foundry alloys. They are used where moderate corrosion resistance, good machinability, moderate strength and ductility, and good castability are required. C83800 has lower mechanical properties but better machinability and lower initial metal cost than C83600.

Both C83600 and C83800 are used for plumbing goods, flanges, feed pumps, meter casings and parts, general household and machinery hardware and fixtures, papermaking machinery, hydraulic and steam valves, valve disks and seats, impellers, injectors, memorial markers, plaques, statuary, and similar products.

Alloys C84400 and C84800 are higher in lead and zinc and lower in copper and tin than C83600 and C83800. They are lower in price, and they have lower tensile strengths and hardnesses. Their widest application is in the plumbing industry.

The leaded yellow brasses C85200 and C85700 are even lower in price and mechanical properties. Their main applications are die castings for plumbing goods and accessories, low-pressure valves, air and gas fittings, general hardware, and ornamental castings. In general, they are best suited for small parts; larger parts with thick sections should be avoided. Aluminum (0.15 to 0.25%) is added to yellow brasses to increase fluidity and to give a smoother surface.

All of the red and yellow general-purpose alloys, when properly made and cleaned, can be plated with nickel or chromium.

Alloys that do not contain lead, such as the tin bronzes C90500 (Navy G bronze) and C90300 (modified Navy G bronze), are considerably more difficult to machine than leaded alloys. Alloys containing 10 to 12% Sn, 1 to 2% Ni, and 0.1 to 0.3% P are known as gear bronzes. Up to 1.5% Pb frequently is added to increase machinability. The addition of lead to C90300 increases machinability, but a concurrent decrease in tin is needed to maintain elongation. The leaded tin bronzes include C92200 (known as steam bronze, valve bronze, or Navy M bronze) and C92300 (commercial G bronze).

All of the tin bronzes are suitable wherever corrosion resistance, leak tightness, or greater strength is required at higher operating temperatures than can be tolerated with leaded red or semired brasses. The limiting temperature for long-time operation of C92200 is 290 °C (550 °F); for C90300, C90500, and C92300, it is 260 °C (500 °F) because of the embrittlement caused by the precipitation of a high-tin phase. This reaction does not occur in tin bronze with tin contents less than ∼8%. For elevated-temperature service in handling fluids and gases, Table UNF-23 of the ASME Boiler and Pressure Vessel Code defines allowable working stresses for C92200 (leaded tin bronze, ASTM B 61) and C83600 (leaded red brass, ASTM B 62) at different temperatures (Table 4).

Table 4 Allowable working stresses for C92200 and C83600 castings

Temperature		Working stress			
		ASTM B 61(a)		**ASTM B 62**(b)	
°C	**°F**	**MPa**	**ksi**	**MPa**	**ksi**
38	100	47	6.8	41	6.0
65	150	47	6.8	41	6.0
93	200	47	6.8	40	5.8
120	250	47	6.8	38	5.5
150	300	45	6.5	34	5.0
175	350	41	6.0	31	4.5
205	400	38	5.5	24	3.5
230	450	34	5.0	24	3.5

260	500	28	4.0	24	3.5
290	550	23	3.3	24	3.5

Source: ASME Boiler and Pressure Vessel Code, Table UNF-23

(a) A minimum tensile strength of 235 MPa (34 ksi) is specified for C92200 in ASTM B 61.

(b) A minimum tensile strength of 250 MPa (30 ksi) is specified for C83600 in ASTM B 62.

Nickel frequently is added to tin bronzes to increase density and leak tightness. Alloys containing more than 3% Ni are heat treatable, but they must contain less than 0.01% Pb for optimum properties; one example of such an alloy is C94700 (88Cu-5Sn-2Zn-5Ni).

Bearing and Wear Properties

Copper alloys have long been used for bearings because of their combination of moderate-to-high strength, corrosion resistance, and self-lubrication properties. The choice of an alloy depends on the required corrosion resistance and fatigue strength, the rigidity of the backing material, lubrication, the thickness of bearing material, load, the speed of rotation, atmospheric conditions, and other factors. Copper alloys can be cast into plain bearings, cast on steel backs, cast on rolled strip, make into sintered powder metallurgy shapes, or pressed and sintered onto a backing material.

Three groups of alloys are used for bearing and wear-resistant applications: phosphor bronzes (Cu-Sn); copper-tin-lead (low-zinc) alloys; and manganese, aluminum, and silicon bronzes.

Phosphor bronzes (Cu-Sn-P or Cu-Sn-Pb-P alloys) have residual phosphorus ranging from a few hundredths of 1% (for deoxidation and slight hardening) to a maximum of 1%, a level that imparts great hardness. Nickel often is added to refine grain size and disperse the lead. Copper-tin bearings have high resistance to wear, high hardness, and moderately high strength. Alloy C90700 is so widely used for gears that it is commonly called gear bronze.

Phosphor bronzes of higher tin content, such as C91100 and C91300, are used in bridge turntables, where loads are high and rotational movement is slow. The maximum load permitted for C91100 (16% Sn) is 17 MPa (2500 psi); for C91300 (19% Sn) it is 24 MPa (3500 psi). These bronzes are high in phosphorus (1% max) to impart high hardness, and low in zinc (0.25% max) to prevent seizing. They are very brittle, and because of this brittleness are sometimes replaced by manganese bronzes or aluminum bronzes.

High-lead tin bronzes are used where a softer metal is required at slow-to-moderate speeds and at loads not exceeding 5.5 MPa (800 psi). Alloys of this type include C93200 and C93700. The former, also known as 83-7-7-3, is an excellent general bearing alloy; it is especially well suited for applications where lubrication may be deficient. Alloy C93200 is widely used in machine tools, electrical and railroad equipment, steel mill machinery, and automotive applications. Alloy C93200 is produced by the continuous casting process and has replaced sand castings for mass-produced bearings of high quality. Alloys C93800 (15% Pb) and C94300 (24% Pb) are used where high loads are encountered under conditions of poor or nonexistent lubrication; under corrosive conditions, such as in mining equipment (pumps and car bearings); or in dusty atmospheres, as in stone-crushing and cement plants. These alloys replace the tin bronzes or low-lead tin bronzes where operating conditions are unsuitable for alloys containing little or no lead. They also are produced by the continuous casting process.

High-strength manganese bronzes have high tensile strength, hardness, and resistance to shock. Large gears, bridge turntables (slow motion and high compression), roller tracks for anti-aircraft guns, and recoil parts of cannons are typical applications.

Aluminum bronzes with 8 to 9% Al are widely used for bushings and bearings in light-duty or high-speed machinery. Aluminum bronzes containing 11% Al, either as-cast or heat treated, are suitable for heavy-duty service (such as valve guides, rolling mill bearings, screw-down nuts, and slippers) and precision machinery. As aluminum content increases above 11%, hardness increases and elongation decreases to low values. Such bronzes are well suited for guides and aligning plates, where wear would be excessive. Aluminum bronzes that contain more than 13% Al exceed 300 HB in hardness but are brittle. Such alloys are suitable for dies and other parts not subjected to impact loads.

Aluminum bronze generally has a considerably higher fatigue limit and freedom from galling than manganese bronze. On the other hand, manganese bronze has great toughness for equivalent tensile strength and does not need to be heat treated.

Electrical and Thermal Conductivity

Electrical and thermal conductivity of any casting will invariably be lower than for wrought metal of the same composition. Copper castings are used in the electrical industry for their current-carrying capacity, and they are used for water-cooled parts of melting and refining furnaces because of their high thermal conductivity. However, for a copper casting to be sound and have electrical or thermal conductivity of at least 85%, care must be taken in melting and casting. The ordinary deoxidizers (silicon, tin, zinc, aluminum, and phosphorus) cannot be used because small residual amounts lower electrical and thermal conductivity drastically. Calcium boride or lithium help to produce sound castings with high conductivity.

Cast copper is soft and low in strength. Increased strength and hardness and good conductivity can be obtained with heat-treated alloys containing silicon, cobalt, chromium, nickel, and beryllium in various combinations. These alloys, however, are expensive and less readily available than the standardized alloys. Table 5 presents some of the properties of these alloys after heat treatment.

Table 5 Composition and typical properties of heat-treated copper casting alloys of high strength and conductivity

UNS No.	Nominal composition	Tensile strength		Yield strength		Elongation, %	Hardness	Electrical conductivity, % IACS
		MPa	**ksi**	**MPa**	**ksi**			
C81400	99Cu-0.8Cr-0.06Be	365	53	250	36	11	69 HRB	70
C81500	99Cu-1Cr	350	51	275	40	17	105 HB	85
C81800	97Cu-1.5Co-1Ag-0.4Be	705	102	515	75	8	96 HRB	48
C82000	97Cu-2.5Co-0.5Be	660	96	515	75	6	96 HRB	48
C82200	98Cu-1.5Ni-0.5Be	655	95	515	75	7	96 HRB	48
C82500	97Cu-2Be-0.5Co-0.3Si	1105	160	1035	150	1	43 HRC	20
C82800	96.6Cu-2.6Be-0.5Co-0.3Si	1140	165	1070	155	1	46 HRC	18

Cost Considerations

During the design of a copper alloy casting, foundry personnel or the design engineer must choose a method of producing internal cavities. There is no general rule for choosing between cored and coreless designs. A cost analysis will determine which is the more economical method of producing the castings, although frequently the choice can be decided by experience.

For example, costs were compared for producing a small (13 mm, or $\frac{1}{2}$ in.) valve disk both as a cored casting and as a machined casting (internal cavities made without cores). The machined casting could be produced for about 78% of the cost of making the identical casting using dry sand cores--a savings of 22% in favor of machined casting. In a similar instance, producing a larger (38 mm, or 1$\frac{1}{2}$ in.) valve disk as a cored casting that required only a minimal amount of machining saved more than 8% in overall cost compared to producing the same valve disk without cores. Thus, for two closely related parts, a difference in manufacturing economy may exist when all cost factors are taken into account.

Copper Powder Metallurgy Products

Introduction

COPPER-BASE POWDER METALLURGY (P/M) products rank second after iron and steel productsin terms of volume. According to the Metal Powder Industries Federation (MPIF), the estimated shipments of copper and copper-base alloy powders in 1996 were ~20,500 Mg (23,000 short tons) in North America. The shipments in Europe were estimated to be ~14,000 Mg (15,600 short tons), while the shipments in Japan were estimated at ~6,200 Mg (7,000 short tons).

The use of copper in the P/M industry dates back to the 1920s, when commercial porous bronze bearings were developed independently in the research laboratories of General Motors Corp. and Bound-Brook Oilless Bearing Co. These self-lubricating bearings still account for the major portion of P/M copper and copper alloy applications. Other important applications for copper and copper-base P/M materials include friction materials, brushes, filters, structural parts, electrical parts, additives to iron powders (alloying as well as infiltration), catalysts, paints, and pigments.

In general, physical and mechanical properties of near full (theoretical) density copper and copper alloy P/M structural parts are comparable to cast and wrought copper-base materials of similar composition. However, P/M copper parts vary in density from the low density typical of self-lubricating bearings or filters to the near full density of electrical parts. The physical and mechanical properties depend greatly on the density as a percentage of theoretical density.

Powder Production and Properties

Copper Powders

Copper powders of 99+ % purity are commercially available. The four major methods of producing such copper powders are:

- Atomization
- Oxide reduction
- Hydrometallurgy
- Electrolysis

Of the previous methods, atomization and oxide reduction are presently practiced on a large scale globally. Hydrometallurgical and electrolytic copper powders have not been manufactured in the United States since the early 1980s, and will not be described further. Information on copper powders produced by hydrometallurgy or electrolysis can, however, be found in Volume 7, *Powder Metallurgy,* of the *ASM Handbook.*

Table 1 shows a comparison of some of the typical fundamental powder characteristics of commercial copper powders made by the four production processes. Each process produces a unique particle shape and surface area.

Table 1 Characteristics of commercial copper powders

Type of powder	Composition, %			Particle shape	Surface area
	Copper	**Oxygen**	**Acid insolubles**		
Electrolytic	99.1-99.8	0.1-0.8	0.03 max	Dendritic	Medium to high
Oxide reduced	99.3-99.6	0.2-0.6	0.03-0.1	Irregular; porous	Medium
Water atomized	99.3-99.7	0.1-0.3	0.01-0.03	Irregular to spherical; solid	Low
Hydrometallurgical	97-99.5	0.2-0.8	0.03-0.8	Irregular agglomerates	Very high

Atomization. In this process, molten copper flows through a refractory nozzle, and the liquid stream is disintegrated into droplets by an impinging jet of water or gas. The droplets solidify into powder particles. The size and shape of these particles are governed by the atomizing medium, pressure, and flow rate. Gas atomization produces spherical particles while the shape of water-atomized powder particles can be controlled from almost spherical to irregular by controlling the interaction between the water jet and the metal stream (Fig. 1). Higher pressures and lower flow rates favor finer powders; average particle sizes less than 325 mesh (45 μm) are feasible.

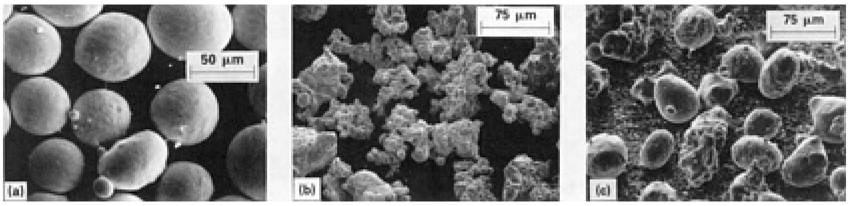


Fig. 1 Scanning electron micrographs of gas- and water-atomized copper powders. (a) Nitrogen atomized. (b) Water atomized, apparent density of 3.04 g/cm^3. (c) Water atomized, apparent density of 4.60 g/cm^3

Water is the preferred atomizing medium for producing copper powder. The atomized powder is often subjected to an elevated temperature reduction (to reduce any oxides formed during atomization) and agglomeration treatment to improve the compacting properties. Table 2 shows the typical properties of commercial water-atomized copper powders.

Table 2 Properties of commercial grades of water-atomized copper powders

Copper, %	Chemical properties, %		Physical properties						
	Hydrogen loss	**Acid insolubles**	**Hall flow rate, s/50 g**	**Apparent density, g/cm^3**	**Tyler sieve analysis, %**				
					+100	**-100+150**	**-150+200**	**-200+325**	**-325**
99.65[(a)]	0.28	. . .	. . .	2.65	Trace	0.31	8.1	28.2	63.4
99.61[(a)]	0.24	. . .	. . .	2.45	0.2	27.3	48.5	21.6	2.4

99.43[(a)]	0.31	. . .	. . .	2.70	Trace	0.9	3.2	14.2	81.7
>99.1[(b)]	<0.35	<0.2	-50	2.4	<8	17-22	18-30	22-26	18-38

(a) Water atomized plus reduced.

(b) Contains magnesium

Oxide Reduction. This process involves oxidizing copper (particulate copper scrap, electrolytic copper, atomized copper, etc.) and milling the oxide into powder. The oxide powder is reduced at elevated temperature by solid or gaseous reducing agents, and the resulting sintered cake is milled into powder. The particle size is controlled through milling of the starting oxide and the reduced sinter cake. The milled copper powder particles are irregular and porous (Fig. 2). A broad range of pore characteristics can be obtained by controlling the reduction conditions.

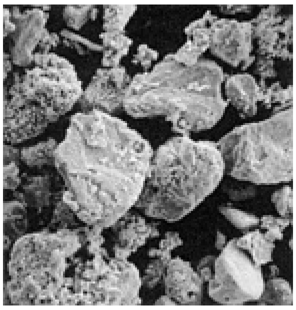


Fig. 2 Oxide-reduced copper powder. 500×

The particle size, shape, and pore characteristics determine the compacting properties of the powder and the part produced. Table 3 shows the typical properties of a commercial copper powder produced by the oxide-reduction process.

Table 3 Properties of commercial grades of copper powder produced by the oxide reduction process

Copper	Chemical properties, %					Physical properties							Compacted properties		
	Tin	**Graphite**	**Lubricant**	**Hydrogen loss**	**Acid insolubles**	**Apparent density, g/cm^3**	**Hall flow rate, s/50 g**	**Tyler sieve analysis, %**					**Green density, g/cm^3**	**Green strength, MPa (psi), at:**	
								+100	**+150**	**+200**	**+325**	**-325**		**165 MPa (12 tsi)**	**6.30 g/cm^3**
99.53	. . .	. . .	. . .	0.23	0.04	2.99	23	0.3	11.1	26.7	24.1	37.8	6.04	6.15 (890)	. . .
99.64	. . .	. . .	. . .	0.24	0.03	2.78	24	. . .	0.6	8.7	34.1	56.6	5.95	7.85 (1140)(a)	. . .
99.62	. . .	. . .	. . .	0.26	0.03	2.71	27	. . .	0.3	5.7	32.2	61.8	5.95	9.3 (1350)(a)	. . .
99.36	. . .	. . .	. . .	0.39	0.12	1.56	. . .	0.1	1.0	4.9	12.8	81.2	5.79	21.4 (3100)(a)	. . .
99.25	. . .	. . .	. . .	0.30	0.02	2.63	30	0.08	7.0	13.3	16.0	63.7	. . .	. . .	8.3 (1200)(a)
90	10	. . .	0.75	. . .	. . .	3.23	30.6	0.0	1.4	9.0	32.6	57.0	6.32	. . .	3.80 (550)
88.5	10	0.5	0.80	. . .	. . .	3.25	12(b)	. . .	. . .	. . .	. . .	. . .	. . .	. . .	3.6 (525)

(a) Measured with die wall lubricant only.

(b) Carney flow

Copper Alloy Powders

Alloy powders are available in various compositions, including brasses, nickel silvers, tin bronzes, aluminum bronzes, and beryllium bronzes. Alloy powders are produced by one of two methods:

- Preblending copper powders with other elemental powders such as tin, zinc, or nickel
- Prealloying during powder production

Preblending. Preblended powders are mixtures of selected compositions, with or without lubricant, that form the desired alloy during sintering. The most common P/M copper alloy made with preblended powders is tin bronze used in self-lubricating bearings. Typical bronze composition is 90Cu-10Sn, often containing up to 1.5% graphite. Some "dilute" bronze bearings contain various amounts of iron replacing some of the copper and tin. Copper-lead and steel-backed copper-lead-tin materials, used to replace solid bronze bearings, also use preblended powders because lead is virtually insoluble in copper and cannot be prealloyed. Friction materials used in brakes and clutches contain disparate materials such as copper with several other components including lead, tin, iron, graphite, molybdenum disulfide, oxides, etc. These can only be made using preblended powders.

Prealloying. Prealloyed powders are generally produced by melting the constituents to form a homogeneous alloy and atomizing the alloy melt by the methods similar to those used for the production of copper powder. They can also be produced by sintering preblended powders and grinding the materials to attain the desired powder characteristics.

Brass and Nickel Silver. Air atomization is generally used for making prealloyed powders of brass and nickel silver for use in high-density (>7.0 g/cm^3) components. The low-surface tension of the molten alloys of these compositions renders the particle shape sufficiently irregular to make the powders compactible (Fig. 3). Reduction of oxides is not necessary for the standard P/M grades of brass and nickel-silver powders.

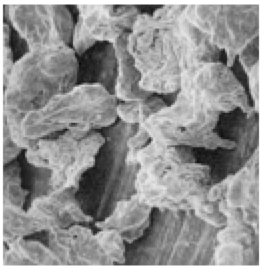


Fig. 3 Prealloyed air-atomized, nickel-silver powder (63Cu-18Ni-17Zn-2Pb). 165×

Commercial prealloyed brass and nickel-silver powders are available in leaded and nonleaded compositions. Commercial brass alloys range from 90Cu-10Zn to 65Cu-35Zn. Leaded versions of 80Cu-20Zn and 70Cu-30Zn are most commonly used for the manufacture of sintered structural parts that may require secondary machining operations. The only commercially available nickel-silver powder has a nominal composition of 65Cu-18Ni-17Zn, which is modified by addition of lead when improved machinability is required.

Bronze. Prealloyed bronze powders are not used widely for structural parts fabrication because their modular particle form and high apparent density result in low green strength. However, blends of such powders with irregular copper powders and phosphorus-copper yield sintered parts with good mechanical properties.

Table 4 shows typical properties of commercial grades of prealloyed brass, bronze, and nickel-silver powders.

Table 4 Physical properties of typical brass, bronze, and nickel-silver alloy compositions

Property	Brass[(a)]	Bronze[(a)]	Nickel silver (a)(b)
Sieve analysis, %			
+100 mesh	2.0 max	2.0 max	2.0 max
-100+200	15-35	15-35	15-35
-200+325	15-35	15-35	15-35
-325	60 max	60 max	60 max
Physical properties			
Apparent density	3.0-3.2	3.3-3.5	3.0-3.2
Flow rate, s/50 g	24-26	. . .	. . .
Mechanical properties			
Green density(c) at 415 MPa (30 tsi), g/cm^3	7.6	7.4	7.6
Green strength(c) at 415 MPa (30 tsi), MPa (psi)	10-12 (1500-1700)	10-12 (1500-1700)	9.6-11 (1400-1600)

(a) Nominal mesh sizes, brass, -60 mesh; bronze, -60 mesh; nickel silver, -100 mesh.

(b) Contains no lead.

(c) Compressibility and green strength data of powders lubricated with 0.5% lithium stearate

Production of Parts

Powder Consolidation

Copper and copper alloy powders are generally cold compacted in closed dies with top and bottom punches used to apply the desired pressure. During cold compaction the powder particles mechanically interlock with each other. Typical compacted densities are 80 to 90% of the theoretical density of the material. When higher densities are required, consolidation methods such as hot pressing, extrusion, hot isostatic pressing, and hot forging are used.

Sintering

The compacted parts are sintered at elevated temperatures under protective conditions to avoid oxidation. During this process the powder particles are metallurgically bonded to each other. Typical sintering times and temperatures for copper P/M parts production are given in the following paragraphs.

Pure Copper P/M Parts

Pure copper P/M parts are used mainly in electrical and electronic applications because of their high-electrical conductivity. It is essential to use very pure copper powders (≥99.95% purity) or to bring about the precipitation of soluble impurities during sintering. As little as 0.023% Fe in solid solution in copper lowers the conductivity to 86% of that of pure copper. Small amounts of iron mechanically mixed with the copper powder lower the conductivity much less, unless the iron dissolves in the copper during sintering. If high-purity copper is used, or if soluble impurities are precipitated during sintering, it is possible to obtain the strength and conductivity values shown in Fig. 4.

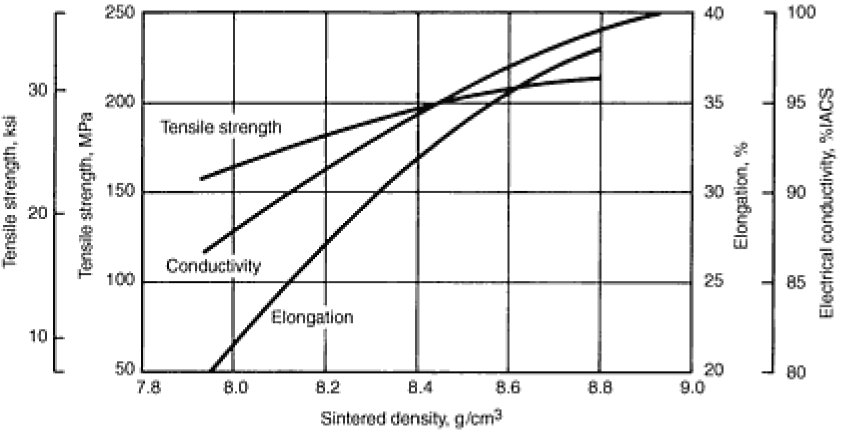


Fig. 4 Effect of density on electrical conductivity and tensile properties of P/M copper

Conductivity is directly related to porosity; the greater the void content (lower the density), the lower the conductivity. Electrical conductivity of pure copper parts pressed at moderate pressures of 205 to 250 MPa (15 to 18 tsi) and sintered at 800 to 900 °C (1500 to 1650 °F) varies from 80 to 90% International Annealed Copper Standard (IACS) on a scale where conductivity of solid annealed copper is 100% IACS. The conductivity of solid copper can be reached or approached in P/M copper parts by sintering the pressed parts at higher temperatures, such as 930 to 1030 °C (1700 to 1900 °F), followed by repressing, coining, or forging.

Typical applications of pure copper parts in which high electrical conductivity is required include commutator rings, contacts, shading coils, nose cones, and electrical twist-type plugs. Copper powders also are used in copper-graphite compositions that have low contact resistance, high current-carrying capacity, and high-thermal conductivity. Typical applications include brushes for motors and generators and moving parts for rheostats, switches, and current-carrying washers.

Bronze P/M Parts

Powder metallurgy bronzes typically originate as premixes consisting of elemental copper and tin powders plus 0.5 to 0.75% dry organic lubricants such as stearic acid or zinc stearate. Some structural parts, however, requiring densities >7.0 g/cm^3 are fabricated from prealloyed powders. Prealloyed powders have higher yield strengths and work hardening rates than premixed powders. Therefore, pressing loads required to achieve given green densities in prealloyed powders are higher than the pressure required for elemental powders. Differences in pressing characteristics of premixed and prealloyed powders are compared in Fig. 5.

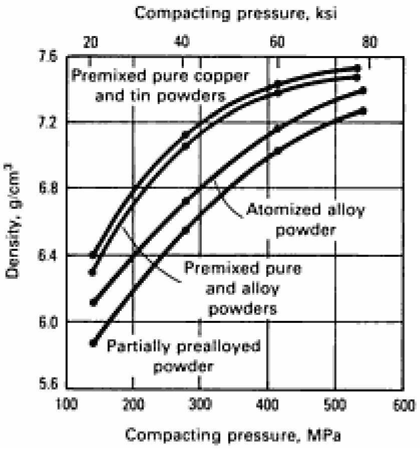


Fig. 5 Pressing characteristics of premixed and prealloyed 90Cu-10Sn powders

Typical sintering furnace temperatures for bronze range from 815 to 870 °C (1500 to 1600 °F); total sintering time within the hot zone can range from 15 to 30 min depending on the furnace temperature selected, required dimensional change, and most importantly, the presence of an optimum alpha-bronze grain structure. Sintering atmospheres should be protective and reducing to facilitate sintering. Reduction of the copper oxides that may surround each copper powder particle and of tin oxide allow for increased diffusion rates. Figure 6 shows typical strength/density data for 90Cu-10Sn sintered bronzes with and without graphite additions. Control of sintered dimensions in premix systems is achieved by manipulating sintering time and/or temperature.

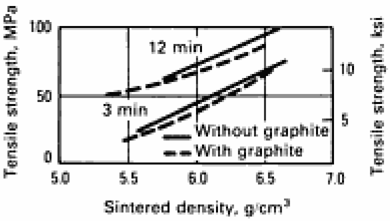


Fig. 6 Effect of density on the strength of copper-tin and copper-tin-graphite compacts

Generally, copper-tin blends composed of relatively coarser powders sinter to high-growth values than a blend composed of finer powders. After powder blends have been tested and adjusted to provide an approximation of target dimensions, final adjustments are made during production sintering to obtain dimensional precision. Factors affecting the ultimate dimensional values include physical characteristics of the constituents and compacted density.

Bearings. Self-lubricating porous bronze bearings continue to consume the major portion of the copper powder produced each year. These bearings are made by pressing elemental powder blends of copper and tin, followed by sintering. The most widely used bearing material is 90Cu-10Sn bronze, often with the addition of up to 1.5% graphite. So-called dilute bronze bearings contain various amounts of iron. Dilution with iron reduces the cost of a bearing at the expense of some loss in performance.

Compaction pressures for the bronze powders range from ~140 to 415 MPa (20 to 60 ksi). Sintering is typically completed in a continuous mesh-belt furnace at temperatures between 815 and 870 °C (1500 and 1600 °F) for ~3 to 8 min at temperature. Typical furnace atmospheres are dissociated ammonia or endothermic gas. To obtain reproducible sintering results it is important to carefully control time and temperature because of their influence on the kinetics of the homogenization process, which in turn determines the dimensional changes occurring during sintering. Most bearings are sized for improved dimensional accuracy; typical sizing pressure can range from ~200 to 550 MPa (30 to 80 ksi). Bearings are sold either dry or saturated with oil. The pores are filled with oil by a vacuum impregnation process. Most common bearings range in density from 5.8 to 6.6 g/cm^3 dry or 6.0 to 6.8 g/cm^3 oil impregnated. This range corresponds to ~25 to 35% pore volume.

The most common shapes for bronze bearings are simple or flanged bushings, but some have spherical external surfaces. Sizes range from about 0.8 to 75 mm ($\frac{1}{32}$ to 3 in.) in diameter. Sintered bronze bearings are used in automotive components, home appliances, farm, lawn and garden equipment, consumer electronics, business machines, industrial equipment, and portable power tools.

Filters. Filters constitute one of the major applications for porous P/M parts. The ability to achieve close control of porosity and pore size is the main reason filters are made from metal powders. Most producers of nonferrous filters prefer atomized spherical powders with closely controlled particle size to allow production of filters within the desired pore size range. The effective pore size of filters generally ranges from 5 to 125 μm.

Tin bronze is the most widely used P/M filter material, but nickel silver, stainless steel, copper-tin-nickel alloys, and nickel-base alloys also are used. The major advantage of P/M bronze materials over other porous metals is cost. Porous P/M bronze filters can be obtained with tensile strengths ranging from 20 to 140 MPa (3 to 20 ksi) and appreciable ductility, up to 20% elongation. P/M bronze also has the same corrosion resistance as cast bronze of the same composition and thus can be used in a wide range of environments.

Bronze filters usually are made by gravity sintering of spherical bronze powders, which are generally made by atomization of molten prealloyed bronze. These powders typically contain 90 to 92% Cu and 8 to 10% Sn. Filters made from atomized bronze have sintered densities ranging from 5.0 to 5.2 g/cm^3. To produce filters with the highest permeability for a given maximum pore size, powder particles of a uniform particle size must be used.

Powder metallurgy bronze filters are commonly used to filter gases, oils, refrigerants, and chemical solutions. They have been used in fluid systems of space vehicles to remove particles as small as 1 μm . Bronze diaphragms can be used to separate air from liquid or mixtures of liquids that are not emulsified. Only liquids capable of wetting the pore surface can pass through the porous metal part.

Bronze filter materials can also be used as flame arrestors on electrical equipment operating in flammable atmospheres, where the high-thermal conductivity of the bronze prevents ignition. They can also be used as vent pipes on tanks containing flammable liquids. In these applications, heat is conducted away rapidly so that the ignition temperature is not reached.

Structural Parts. Powder metallurgy bronze parts for structural applications frequently are selected because of corrosion and wear resistance of bronze. They are generally produced by methods similar to those used for self-lubricating bearings and are generally used in automobile clutches, copiers, outboard motors, and paint-spraying equipment. Typical compositions of bronze structural parts (CT-1000) are included in Table 5 and the typical properties are shown in Table 6.

Table 5 Typical compositions of copper-base P/M structural parts

Material designation	Chemical composition, %					
	Cu	**Zn**	**Pb**	**Sn**	**Ni**	**Element**
CZ-1000	88.0	bal	. . .	. . .	. . .	Minimum
	91.0	bal	. . .	. . .	. . .	Maximum
CZP-1002	88.0	bal	1.0	. . .	. . .	Minimum

	91.0	bal	2.0	. . .	. . .	Maximum
CZ-2000	77.0	bal	. . .	. . .	. . .	Minimum
	80.0	bal	. . .	. . .	. . .	Maximum
CZP-2002	77.0	bal	1.0	. . .	. . .	Minimum
	80.0	bal	2.0	. . .	. . .	Maximum
CZ-3000	68.5	bal	·	. . .	. . .	Minimum
	71.5	bal	. . .	. . .	. . .	Maximum
CZP-3002	68.5	bal	1.0	. . .	. . .	Minimum
	71.5	bal	2.0	. . .	. . .	Maximum
CNZ-1818	62.5	bal	. . .	·	16.5	Minimum
	65.5	bal	. . .	. . .	19.5	Maximum
CNZP-1816	62.5	bal	1.0	. . .	16.5	Minimum
	65.5	bal	2.0	. . .	19.5	Maximum
CT-1000	87.5	bal	. . .	9.5	. . .	Minimum
	90.5	bal	. . .	10.5	. . .	Maximum

Note: Total by difference equals 2.0% maximum, which may include other minor elements added for specific purposes. Source: MPIF Standard 35 (1997 Edition)

Table 6 Properties of copper-base P/M structural materials

Material designation code(a)	Minimum yield strength		Typical values										Unnotched Charpy impact energy		Compressive yield strength (0.1%)		Density, g/cm^3	Apparent hardness, HRH
			Ultimate tensile strength		**Yield strength (0.2%)**		**Elongation in 25 mm (1 in.), %**	**Young's modulus**		**Transverse rupture strength**								
	MPa	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**		**GPa**	**10^6 psi**	**MPa**	**ksi**		**J**	**ft · lbf**	**MPa**	**ksi**		
CZ-1000-9	60	9	120	17	70	10	9.0	80	12	270	39		20	14.8	80	12	7.6	65
CZ-1000-10	70	10	140	20	80	12	10.5	90	13	320	46		33	24.3	80	12	7.9	72
CZ-1000-11	80	11	160	23	80	12	12.0	100	14.5	360	52		42	31.0	80	12	8.1	80
CZP-1002-7	50	7	140	20	60	9	10.0	90	13	310	45		33	24.3	70	10	7.9	66
CZ-2000-11	80	11	160	23	90	13	9.0	. . .	. . .	360	52		37	27.3	. . .	. . .	7.6	73
CZ-2000-12	80	12	240	35	120	17	18.0	. . .	. . .	480	70		61	45.0	. . .	. . .	8.0	82
CZP-2002-11	80	12	160	23	90	13	9.0	85	12.3	360	52		37	27.3	80	12	7.6	73
CZP-2002-12	80	12	240	35	120	17	18.0	100	14.5	480	70		61	45.0	100	14.5	8.0	82
CZ-3000-14	100	14	190	28	110	16	14.0	80	12	430	62		31	22.9	120	17	7.6	84
CZ-3000-16	110	16	230	33	30	19	17.0	90	13	590	86		52	38.4	130	19	8.0	92

CZP-3002-13	90	13	190	28	100	14.5	14.0	80	12	390	57	16	11.8	80	12	7.6	80
CZP-3002-14	100	14	220	32	110	16	16.0	90	13	490	71	34	25.0	100	14.5	8.0	88
CNZ-1818-17	120	17	230	33	140	20	11.0	95	13.8	500	72.5	33	24.3	170	25	7.9	90
CNZP-1816-13	90	13	180	26	100	14.5	10.0	95	13.8	340	49	50	36.9	120	17	7.9	86
CT-1000-13 (repressed)	90	13	150	22	110	16	4.0	60	8.7	310	50	5	3.7	140	20	7.2	82

Source: MPIF Standard 35 (1997 Edition)

(a) Suffix numbers represent minimum strength values in ksi.

Brass and Nickel Silver P/M Parts

In contrast to bronze structural parts, parts made from brass, leaded brass, and nickel silver are produced from prealloyed atomized powder. Table 5 shows compositions of some common brass and nickel-silver alloys. The leaded compositions are used whenever secondary machining operations are required.

The alloy powders are usually blended with lubricants in amounts from 0.5 to 1.0 wt%. Lithium stearate is the preferred lubricant because of cleansing and scavenging action during sintering. However, bilubricant systems are common, such as lithium stearate and zinc stearate, which minimize the surface staining attributed to excessive lithium stearate. Lubricated powders are typically compacted to 75% of theoretical density at 207 MPa (30 ksi) and to 85% of theoretical density at 415 MPa (60 ksi).

Sintering of brass and nickel-silver compacts is normally performed in protective atmospheres. Dissociated ammonia, endothermic gas, and nitrogen-base atmospheres are most common. Temperatures range from 815 to 925 °C (1500 to 1700 °F) depending on alloy composition. To avoid distortion and/or blistering of the compacts, sintering temperatures should not exceed the solidus temperature of the alloy. Through multiple pressing and sintering operations, yield strength and hardness approaching those of the wrought alloy counterparts can be achieved. To minimize zinc losses during sintering, yet allow for adequate lubricant removal, protective-sintering-tray arrangements are used. Table 6 shows the typical properties of common brass and nickel-silver P/M parts.

Next to bronze bearings, brasses and nickel silvers are the most widely used materials for structural P/M parts. Typical applications include hardware for latch bolts and cylinders for locks; shutter components for cameras; gears, cams, and actuator bars in timing assemblies and in small generator drive assemblies; and decorative trim and medallions. In many of these applications, corrosion resistance, wear resistance, and aesthetic appearance play important roles.

Copper-Nickel P/M Parts

Copper-nickel P/M alloys containing 75Cu-25Ni and 90Cu-10Ni have been developed for coinage and corrosion-resistance applications. The 75Cu-25Ni alloy powder pressed at 772 MPa (112 ksi) has a green density 89% of the theoretical density. After sintering at 1090 °C (2000 °F) in dissociated ammonia, elongation is 14%, and apparent hardness is 20 HRB. Repressing at 772 MPa (112 ksi) increases density to 95%. This alloy has the color of stainless steel and can be burnished to a high luster. The 90Cu-10Ni alloy has a final density of 99.4% under similar pressing and sintering conditions. It has a bright bronze color and also can be burnished to a high luster.

In one method of producing coins, medals, and medallions, a mixture containing 75% Cu and 25% Ni powders is blended with zinc stearate lubricant and compressed, sintered, coined, and re-sintered to produce blanks suitable for striking. These blanks are softer than rolled blanks because they are produced from high-purity materials. Therefore, they can be coined at relatively low pressures, and it is possible to achieve greater relief depth with reduced die wear.

In another procedure, an organic binder is mixed with copper or copper-nickel powders and rolled into "green" sheets. Individual copper and copper-nickel sheets are pressed together to form a laminate, and blanks are punched from it. Blanks are heated in hydrogen to remove the organic binder and sinter the material. The density of the "green" blanks is low (45% of theoretical), but coining increases density to 97%. After pressing, the blanks are annealed to improve ductility and coinability.

Copper-Lead P/M Parts

Copper and lead, which have limited solubilities in each other, are difficult to alloy by conventional ingot metallurgy. Copper-lead powder mixtures have excellent cold pressing properties; they can be compacted at pressures as low as 76 MPa (11 ksi) to densities as high as 80% of theoretical density. After sintering, they can be repressed at pressures as low as 152 MPa (22 ksi) to produce essentially nonporous bearings.

Steel-backed copper or copper-lead-tin P/M materials are sometimes used to replace solid bronze bearings. They are produced by spreading the powder in a predetermined thickness on a steel strip, sintering, rolling to theoretical density, resintering, and annealing. The end product has a residual porosity of ~0.25%. Blanks of suitable size are cut from the bimetallic strip, formed, and drilled with oil holes or machined to form suitable grooves. These materials include Cu-25Pb-0.5Sn, Cu-25Pb-3.5Sn, Cu-10Pb-10Sn, and Cu-50P-1.5Sn alloys.

Copper-Base P/M Friction Materials

Sintered metal-based friction materials are used in applications involving the transmission of motion through friction (clutches), and for deceleration and stopping (brakes). In these applications, mechanical energy is converted into frictional heat, which is absorbed and dissipated by the friction material. Copper-base materials are preferred because of their high thermal conductivity; however, low cost iron-base materials have been developed for moderate to severe duty dry applications.

Most friction materials contain copper powders blended with other metal powders, solid lubricants, oxides, and other compounds. These constituents are immiscible in each other, and therefore, can only be made by powder metallurgy. Table 7 shows compositions of some common copper-base friction materials.

Table 7 Compositions of some common copper-base friction materials

Composition, wt%							Use(a)
Cu	**Sn**	**Fe**	**Pb**	**Graphite**	**MoS_2**	**Other**	
60-75	4-10	5-10	. . .	3-10	3-12	2-7 SiO_2	D
52.5	. . .	. . .	7.5	. . .	. . .	5 SiO_2; 15 Bi	W
72	4.7	3.3	3.5	8.7	1.4	1.9 SiO_2; 0.2 Al_2O_3	W, D
72	7	3	6	6	. . .	3 SiO_2; 4 MoO_3	D
62	7	8	12	7	. . .	4 sand	D
74	3.5	. . .	. . .	16	. . .	2 Sb; 4.5 SiO_2	D

(a) W, wet; D, dry. See Fig. 7.

Mixtures of the appropriate powders are carefully blended to minimize segregation of the constituents. Fine metal powders with high-surface area are necessary to provide a strong and thermally conductive matrix. The blended powders are compacted at pressures ranging from 165 to 275 MPa (24 to 40 ksi).

Bell-type sintering furnaces are used where the friction facing is bonded to a supporting steel backing plate such as in clutch disks. The green disks are placed on the copper-plated steel plates and stacked. Pressure is applied on the vertical stack of disks. Sintering temperatures range from 550 to 950 °C (1020 to 1740 °F) in a protective atmosphere. Typical sintering times are 30 to 60 min. The sintered parts are typically machined for dimensional accuracy and surface parallelism.

The friction elements are usually brazed, welded, riveted, or mechanically fastened to the supporting steel members. They may also be pressure bonded directly to the assembly.

Copper-Base P/M Electrical Contact Materials

Copper-base materials are used in electrical contacts because of their high electrical and thermal conductivities, low cost, and ease of fabrication. Their main drawbacks are poor resistance to oxidation and corrosion. Therefore, copper-base contacts are used in applications where the voltage drop resulting from the oxide film is acceptable or where it is possible to protect the contact, such as by immersion in oil or by enclosing the contact in a protective gas or vacuum.

Common copper alloys used in contacts include yellow brass (C27000), phosphor bronze (C51000), and copper-beryllium alloys (C17200 and C17500). These are made by the melt-cast process and are limited to lower current applications where arcing and welding are not severe.

Composites of copper with refractory metals (Cu-W) or their carbides (Cu-WC) are used in applications in which limited oxidation of the copper is acceptable or where oxidation is prevented by one of the methods mentioned previously. The properties of the contacts depend on the manufacturing method used. The specific method used depends on the composition of the composite. As a general rule-of-thumb, materials with 40% or less tungsten or tungsten carbide are manufactured by the conventional pressing, sintering (generally below the melting point of copper), and repressing technique. Materials containing more than 40% tungsten are generally made by infiltrating the copper into either loose tungsten powder or pressed-and-sintered tungsten compacts. Their counterparts using tungsten carbide are made by infiltrating the copper into loose powder because the tungsten carbide powder cannot be pressed into compacts. Additional information on copper-base electrical contact materials can be found in the Section "Special-Purpose Materials" in this Handbook.

Copper-Base P/M Brush Materials

Brushes are components that transfer electrical current between the stationary and rotating elements in electric motors and generators. Most common brushes are made from composites of graphite and a conductive metal. The graphite provides the required lubrication and the metal provides the current-carrying capability; copper and silver are preferred metals because of their high-electrical conductivity.

The copper content in typical copper-graphite brush materials varies from ~20 to 75%, with the balance being graphite. Powder metallurgy is the only way to produce these materials because of the immiscibility of the two components. Copper powder used in the brushes could be made by oxide reduction, electrodeposition, atomization, or flaking.

The manufacture of brushes involves blending the copper and graphite powders. These are molded into brushes or large blocks, typically at pressures ranging from 100 to 200 MPa (15 to 30 ksi), providing green densities of 2 to 4 g/cm^3. The molded parts are sintered at 500 to 800 °C (950 to 1500 °F) in a protective atmosphere. Machining is performed if necessary to achieve the final dimensional tolerances.

Copper-graphite brushes are widely used in battery-powered tools that require high power outputs in small, lightweight packages. Typically, input voltage influences the metal content required. High voltages require a low-metal content whereas low voltages require a high-metal content. Below 9 V, the metal content is usually higher than 80% while above 18 V, the metal content is generally below 50%.

Copper-graphite brushes are also used extensively in automotive applications including starter motors, blower motors, doorlocks, and windshield wiper motors. The starter motors generally used high-copper content grades to enable them to handle extremely high-current densities for short periods of time. Blower motors use lower-copper content grades to extend service life to several thousand hours. The doorlocks and windshield wiper motors use grades that are between the blower and starter motor grades.

Infiltrated Parts

Iron-base P/M parts can be infiltrated with copper or a copper alloy by placing a slug of the infiltrant on the part and then sintering above the melting point of the infiltrant. The molten infiltrant is completely absorbed in the pores by capillary action and a composite structure is created. The amount of infiltrant used is limited by the pore volume in the starting iron part and typically ranges between 15 and 25%.

Infiltration increases the density of the part, resulting in improved mechanical properties, corrosion resistance, electrical and thermal conductivities, machinability, and brazeability. Tensile strengths ranging from 480 to 620 MPa (70 to 90 ksi) can be achieved in iron-base parts infiltrated with 15 to 25% copper.

Infiltration is used for iron-base structural parts that much have densities >7.4 g/cm^3. Typical examples include gears, automatic transmission components, valve seat inserts, automobile door hinges, etc.

Oxide-Dispersion-Strengthened Copper P/M Materials

Copper is widely used in industry because of high electrical and thermal conductivities, but it has low strength, particularly when heated to high temperatures. If can be strengthened by using finely dispersed particles of stable oxides such as alumina, titania, beryllia, thoria, or yttria in the matrix. Because these oxides are immiscible in liquid copper, dispersion-strengthened copper cannot be made by conventional ingot metallurgy; powder metallurgy techniques must be used.

Manufacture

Oxide-dispersion-strengthened (ODS) copper can be made by simple mechanical mixing of the copper and oxide powders, by coprecipitation from salt solutions, by mechanical alloying, or by selective or internal oxidation. Dispersion quality and cost vary substantially among these methods; internal oxidation produces the finest and most uniform dispersion. Aluminum oxide is a common dispersoid used in the manufacture of ODS copper.

In internal oxidation, an atomized copper-aluminum alloy is internally oxidized at elevated temperature. This process converts the aluminum into aluminum oxide. Size and uniformity of dispersion of the aluminum oxide depend on several process parameters. Consolidation of the powder to full density and/or various mill forms is accomplished by various techniques. Mill forms, such as rod and bar, are made by canning the powder in a suitable metal container (generally copper) and hot extruding it to the desired size. Wire is made by cold drawing coils of rod. Strip is made either by rolling coils of extruded rectangular bar or by directly rolling powder with or without a metal container. Large shapes that cannot be made by hot extrusion are made by hot isostatic pressing of canned powder; alternatively, such shapes can be made by hot forging canned powder or partially dense compacted preforms.

Properties of the consolidated material depend on the amount of deformation introduced into the powder particles. Consequently, low-deformation processes such as hot isostatic pressing and, to a lesser extent, hot forging develop materials with lower strengths and ductilities than those produced by extrusion.

Finished parts can be made from consolidated shapes by machining, brazing, and soldering. Fusion welding is not recommended because it causes the aluminum oxide to segregate from the liquid copper matrix, resulting in a loss of dispersion strengthening. However, flash welding, in which the liquid metal is squeezed out of the weld joint, and electron beam welding, in which a small heat-affected zone is created, have been used successfully. Solid-state welding (with multiple cold upsets in a closed die) has also been used with success to join smaller coils into a large coil for wire drawing.

Properties

Oxide-dispersion-strengthened copper offers a unique combination of high-strength and high-electrical and thermal conductivities. More important, it retains a larger portion of these properties during and after exposure to elevated temperatures than any other copper alloy.

The properties of ODS copper can be modified to meet a wide range of design requirements by varying the aluminum oxide content and/or the amount of cold work. Figure 7 shows the ranges in tensile strength, elongation, hardness, and electrical conductivity obtained as a function of aluminum/aluminum oxide contents. These properties are typical for rod stock in the hot extruded condition. Cold work can be used to broaden the ranges in tensile strength, elongation, and hardness; the effect on electrical conductivity is minimal.

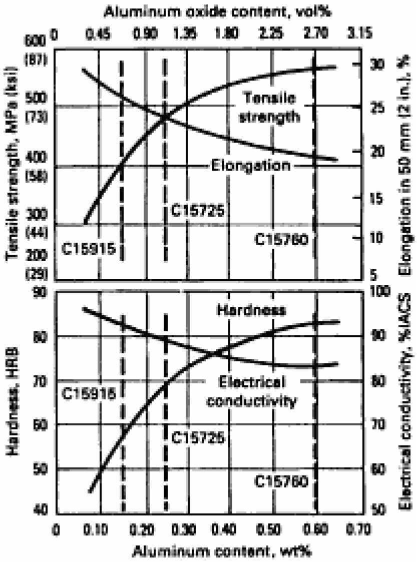


Fig. 7 Properties of three ODS coppers

Three grades of ODS copper are commercially available. They are designated as C15715, C15725, and 15760 by the Copper Development Association Inc. The nominal compositions of these three grades are:

Grade	Copper		Aluminum oxide	
	wt%	**vol%**	**wt%**	**vol%**
C15715	99.7	99.3	0.3	0.7
C15725	99.5	98.8	0.5	1.2
C15760	98.9	97.3	1.1	2.7

The free or reducible oxygen content of the three ODS coppers, generally ~0.02 to 0.05 wt%, is present in the form of dissolved oxygen and cuprous oxide. Alloys in this state are prone to hydrogen embrittlement at high temperatures. Low-oxygen (LOX) compositions are available in all of these grades, at which the reducible oxygen is converted to nonreducible oxide by adding up to 0.020 wt% boron as the oxygen getter. These grades are then immune to hydrogen embrittlement and must be specified for applications in which the components are likely to be subjected to reducing atmospheres during manufacture or use.

Physical Properties. Because ODS copper contains small amounts of aluminum oxide as discrete particles in an essentially pure copper matrix, the physical properties closely resemble those of pure copper. Table 8 shows physical properties of the three commercial ODS coppers comparing them with oxygen-free (OF) copper. The melting point is essentially the same for copper because the matrix melts and the aluminum oxide separates from the melt. Density, modulus of elasticity, and coefficient of thermal expansion are similar to those of pure copper.

Table 8 Physical properties of three oxide-dispersion-strengthened (ODS) coppers and oxygen-free (OF) copper

Property	Material			
	C15715	**C15725**	**C15760**	**OF Copper**
Melting point, °C (°F)	1083 (1981)	1083 (1981)	1083 (1981)	1083 (1981)
Density, g/cm^3 (lb/in.)	8.90 (0.321)	8.86 (0.320)	8.81 (0.318)	8.94 (0.323)
Electrical resistivity at 20 °C (68 °F), Ω· mm^2/m (Ω · circular mil/ft)	0.0186 (11.19)	0.0198 (11.91)	0.0221 (13.29)	0.017 (10.20)
Electrical conductivity at 20 °C (68 °F), %IACS	92	87	78	101
Thermal conductivity at 20 °C (68 °F), W/m · K (Btu/ft · h · °F)	365 (211)	344 (199)	322 (186)	391 (226)
Linear coefficient of thermal expansion for 20 to 1000 °C (68 to 1830 °F), ppm/°C (ppm/°F)	16.6 (9.2)	16.6 (9.2)	16.6 (9.2)	17.7 (9.8)
Modulus of elasticity, GPa (10^6 psi)	130 (19)	130 (19)	130 (19)	115 (17)

High-electrical and thermal conductivities are particularly interesting to design engineers in the electrical and electronics industries. At room temperature, these range from 78 to 92% of those for pure copper. Coupled with the high strengths of these materials, they enhance the current-carrying or heat-dissipating capabilities for given section size and structural strength. Alternatively, they enable reduction of section sizes for component miniaturization without sacrificing structural strength or current and heat-carrying capabilities. At elevated temperatures, the decrease in electrical and thermal conductivities of ODS coppers closely parallel those of pure copper.

Room-Temperature Mechanical Properties. Table 9 shows the room-temperature mechanical properties of ODS C15715 in available mill forms. These cover a wide range of sizes, typified by various amounts of cold work by drawing and rolling, for example. Oxide-dispersion-strengthened copper has strength comparable to many steels and conductivity comparable to copper.

Table 9 Typical room-temperature mechanical properties of C15715

Shapes	Thickness or diameter		Temper or condition(a)	Tensile strength		Yield strength		Elongation, %	Hardness, HRB
	mm	**in.**		**MPa**	**ksi**	**MPa**	**ksi**		
Flat products	10	0.400	A-C	413	60	331	48	20	62
	1.3	0.050	CW 88%	579	84	537	78	7	. . .

	0.6	0.025	CW 94%	620	90	579	84	7	. . .
	0.15	0.006	CW 98%	661	96	613	89	6	. . .
Plate	≤130	5.0	A-C	365	53	255	37	26	62
	25	1.0	CW 60%	476	69	427	62	10	. . .
	16	0.625	CW 75%	483	70	455	66	10	. . .
Rod	29	1.125	A-C	393	57	324	47	27	62
	19	0.75	CW 55%	427	62	407	59	18	68
	7	0.275	CW 94%	496	72	469	68	9	72
Wire	1.3	0.050	CW 99%	524	76	496	72	2	. . .
	1.3	0.050	HT 650 °C	400	58	351	51	10	. . .
	0.4	0.015	CW 99.9%	606	88	579	84	1	. . .
Rounds	≤760	30	A-C	365	53	255	37	26	. . .

(a) A-C, as consolidated; CW, cold work/% reduction in area; HT, heat treatment for 1 h

Oxide-dispersion-strengthened copper has excellent resistance to softening even after exposure to temperatures close to the melting point of copper because the aluminum oxide particles are stable at these temperatures and retain their original size and spacing. These particles block dislocation and grain boundary motion and thus prevent recrystallization, which is normally associated with softening. Figure 8 compares the softening behavior of C15715 strip with OF Copper (C10200) and a copper-zirconium (C15000) alloy. At common brazing and glass-to-metal sealing temperatures (above 600 °C, or 1110 °F) encountered in practice, ODS coppers retain much of their strength while OF copper and copper-zirconium lose most of their strength. Therefore, ODS copper is used in applications in which the component manufacture involves high-temperature operations such as brazing, glass-to-metal sealing, hot isostatic pressing, diffusion bonding, etc.

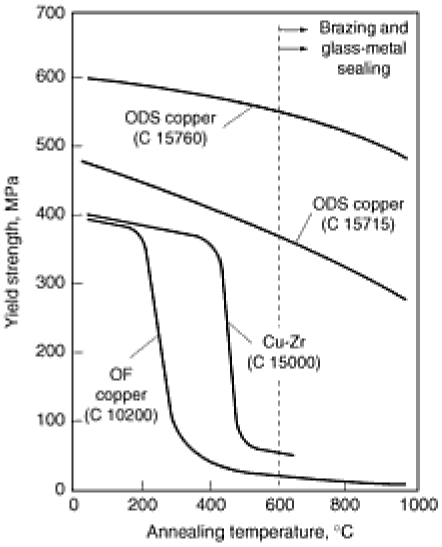


Fig. 8 Softening behavior of oxide-dispersion-strengthened (ODS) coppers compared to oxygen-free (OF) copper and copper-zirconium alloy

Elevated-Temperature Mechanical Properties. ODS copper has excellent strength at elevated temperatures. Figure 9 shows the 100 h stress-rupture strengths of C15760 and C15715 at temperatures up to 870 °C (1600 °F). Other high-conductivity copper-base materials are shown for comparison. Ranging from pure copper on the low end to precipitation-hardened alloys on the high end, there is a sharp drop in stress-rupture strength in the 200 to 450 °C (400 to 850 °F) temperature range. Above 400 °C (750 °F), the ODS coppers are superior to any of the other alloys. Above 600 °C (1100 °F), the ODS coppers have rupture strengths comparable or superior to some stainless steels. Oxide-dispersion-strengthened copper has excellent thermal stability at high temperatures because the aluminum oxide particles retain their original particle size and spacing even after prolonged heating and do not allow recrystallization of the matrix. Cold work significantly enhance the stress-rupture properties of ODS copper; the higher the temperature, the more noticeable the enhancement.

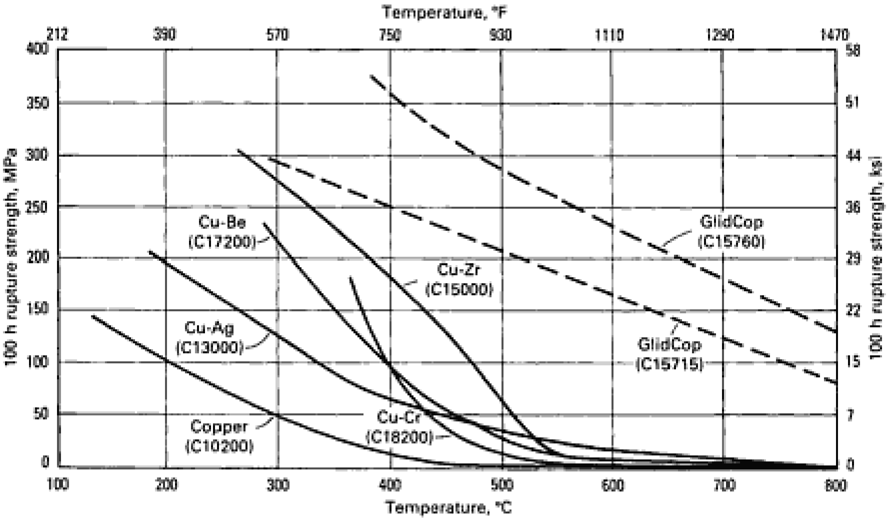


Fig. 9 Elevated-temperature stress-rupture properties of oxide-dispersion-strengthened copper compared to several high-conductivity copper alloys

Applications

The combination of high-electrical and thermal conductivity, outstanding corrosion resistance, ease of fabrication, and retainment of high strength at elevated temperatures make ODS copper useful in many applications. Dispersion-strengthened copper enhances the current-carrying or heat-dissipating capabilities for a given section size and structural strength. Alternatively, it enables reduction of section sizes for component miniaturization. Major application areas include:

- Resistance welding electrodes
- Metal inert gas (MIG) welding contact tips
- Lead wires for incandescent lamps
- X-ray and microwave tube components
- Relay blades and contact supports
- Sliding electrical contacts
- Particle accelerator components used for physics and materials research
- Hybrid circuit package components
- Electrodes for electrical discharge machining (EDM) operations

Thermal Softening and Stress Relaxation in Copper

Introduction

COPPER AND COPPER ALLOYS are used extensively in structural applications in which they are subject to moderately elevated temperatures. Examples include automotive radiators, solar heating panels, communications cable, and electrical connectors. At relatively low operating temperatures, these alloys can undergo thermal softening (degradation of strength/hardness) or stress relaxation (decrease in stress resulting from transformation of elastic strain into plastic strain in a constrained solid), which can lead to service failures. Because of the wide variations in composition and processing among commercial copper alloys, resistance to thermal softening and stress relaxation varies considerably. Of course, selection of an alloy for a given application is based not only on stress-time temperature response but also on such factors as cost, basic mechanical and physical properties, operating temperature, service environment, and formability. For many applications, electrical conductivity is a primary consideration.

Thermal Softening Data

At temperatures lower than those inducing recrystallization in commercial heat treatments, thermal softening can occur over extended periods. If resistance to softening at slightly elevated temperature is required, C11100 is often specified. This copper contains a small amount of cadmium, which raises the temperature at which recovery and recrystallization occur. Oxygen-free copper, electrolytic tough pitch copper, and fire-refined tough pitch copper are available as silver-bearing coppers having specific minimum silver contents. The silver, which may be present as an impurity in anode copper or may be intentionally alloyed to molten cathode copper, also imparts resistance to softening to cold-worked metal. Silver-bearing coppers and cadmium-bearing coppers are used for applications such as automotive radiators and electrical conductors that must operate at temperatures above about 200 °C (400 °F).

Adding small amounts of elements such as silver, cadmium, iron, cobalt, and zirconium to deoxidized copper imparts resistance to softening at the times and temperatures encountered in soldering operations, such as those used to join components of automobile and truck radiators, and those used in semiconductor packaging operations. Thermal and electrical conductivities and room-temperature mechanical properties are unaffected by small additions of these elements. However, cadmium-copper and zirconium-copper work harden at higher rates than either silver-bearing copper or electrolytic tough pitch copper.

Cold-rolled silver-bearing copper is used extensively for automobile radiator fins. Usually such strip is only moderately cold rolled because heavy cold rolling makes silver-bearing copper more likely to soften during soldering or baking operations. Some manufacturers prefer cadmium-copper C14300 because it can be severely cold rolled without making it susceptible to softening during soldering. Figure 1 illustrates the softening characteristics of C14300 and C11400 as measured for several temperatures and two tempers. As shown in Fig. 1(b), C14300 cold rolled to a tensile strength of 400 MPa (64 ksi) retains 91% strength after a typical core bake of 3 min at 345 °C (650 °F). Silver-bearing copper C11400 given the same cold reduction retains only 60% tensile strength after the same baking schedule.

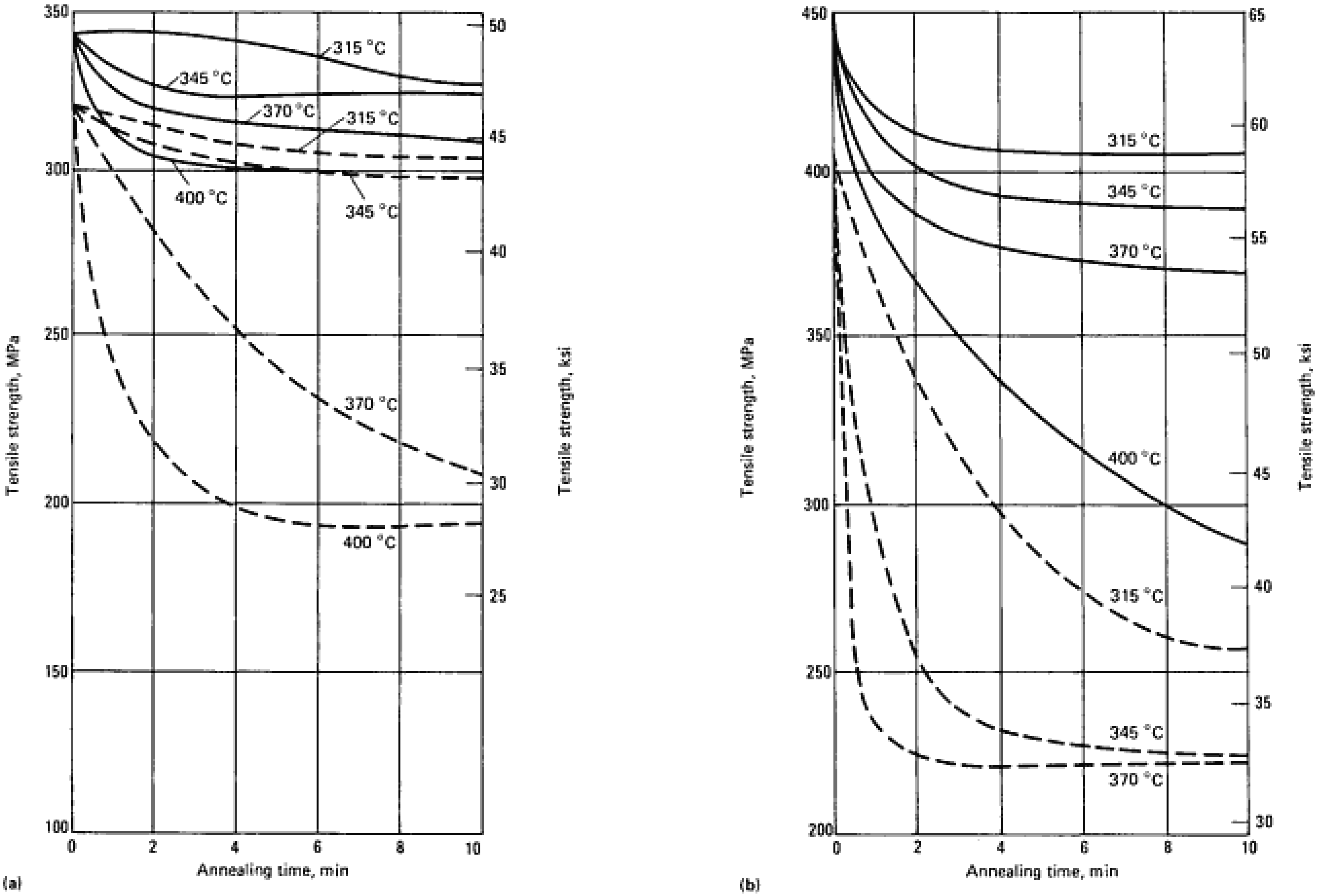


Fig. 1 Softening characteristics of cadmium-bearing copper (C14300 represented by solid curves) and silver-bearing tough pitch copper (C11400 represented by dashed curves). (a) Softening curves for material cold reduced 21% in area, from 0.1 to 0.075 mm (0.0038 to 0.0030 in.) in thickness. (b) Softening curves for material cold reduced 90% in area, from 0.75 to 0.075 mm (0.0300 to 0.0030 in.) in thickness

Another application in which softening resistance is of paramount importance is lead frames for electronic devices, such as plastic dual-in-line packages. During packaging and assembly, lead frames may be subjected to temperatures up to 350 °C (660 °F) for several minutes and up to 500 °C (930 °F) for several seconds. The leads must maintain good strength because they are pressed into socket connectors, often by automated assembly machines; softened leads collapse, causing spoilage.

Alloy C15100 (copper-zirconium), alloy C15500 (copper-silver-magnesium-phosphorus), alloy C19400 (copper-iron-phosphorus-zinc), and alloy C19500 (copper-iron-cobalt-tin-phosphorus) are popular for these applications because they have good conductivity, good strength, and good softening resistance. Figures 2 and 3 compare the softening resistance of these alloys with electrolytic copper C11000.

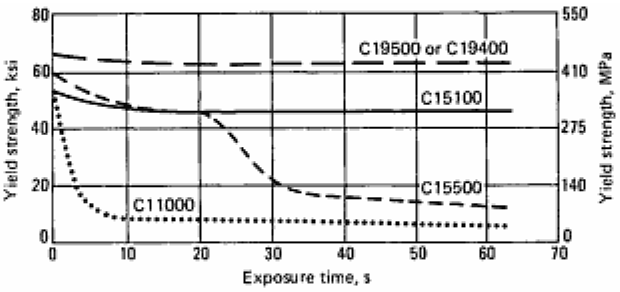


Fig. 2 Softening resistance of lead frame materials at the upper temperature limit (500 °C, or 930 °F)

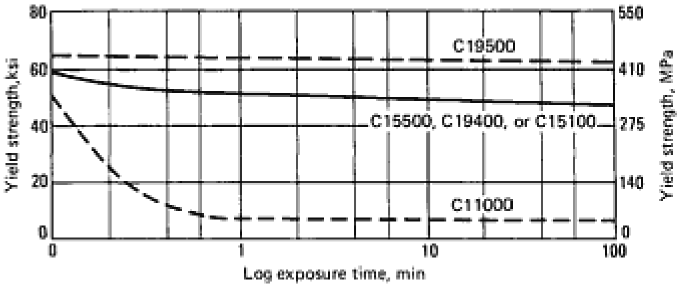


Fig. 3 Softening resistance of lead frame materials at an intermediate temperature level (350 °C, or 660 °F)

Stress-Relaxation Data

When an external stress is applied to a piece of metal, it reacts by developing an equal and opposite internal stress. If the metal is held in this strained position, the internal stress will decrease as a function of time. This phenomenon is called stress relaxation and happens because of the transformation of elastic strain in the material to plastic, or permanent strain. The reduction-of-stress rate will be a function of alloy, temper, temperature, and time.

Unalloyed copper C11000 (electrolytic tough pitch) is probably the most inexpensive high-conductivity copper and is used extensively because of the ease of fabrication. The stress-relaxation behavior of this material is rather poor, as demonstrated in Fig. 4, in which relaxed stress is plotted as a function of time and temperature for 0.25 mm (0.010 in.) C11000 wire initially stressed in tension to 89 MPa (13 ksi). Comparison of stress values at a given time for different temperatures illustrated the very sharp dependence of stress relaxation on temperature for this copper. At 93 °C (200 °F), for example, no tension remains after 10^5 h (11.4 years), whereas 40% of the initial stress remains after 40 years at room temperature. For C11000 and for many other copper metals, stress relaxation in a given time period is inversely proportional to absolute temperature (Ref 1).

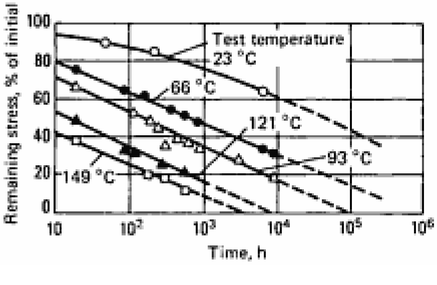


Fig. 4 Tensile-stress-relaxation characteristics of C11000. Data are for tinned 30 AWG (0.25 mm diam) annealed ETP copper wire; initial elastic stress, 89 MPa (13 ksi).

The stress-relaxation behavior of C10200 (oxygen-free copper) is somewhat better than that of C11000, as shown in Table 1, which also presents stress-relaxation data for other high-conductivity copper metals. A more extensive comparison of the mechanical behavior of C10200 and C11000 is presented in Ref 2.

Table 1 10,000 h tensile-stress-relaxation data for selected types of tinned copper wire

Alloy	Temper	Temperature		Initial stress(a)		Stress remaining, %
		°C	**°F**	**MPa**	**ksi**	
C10200	O61	27	80	82	11.9	69
C11000	O61	23	73	89	12.9	60
C15000	H04(b)	23	73	203	29.5	93

(a) Initial stress set at ~55% of 0.2% offset yield strength.

(b) In-process strand anneal.

(c) Batch annealed.

Among the high-conductivity coppers, relaxation is greatest in very-high-purity copper (99.999+%)--a material used mainly in research. Improvement in the stress-relaxation behavior of high-conductivity copper can be achieved by adding alloying elements that cause solid-solution strengthening, age hardening, or dispersion hardening (Ref 3). For example, minute additions of silver significantly reduce stress relaxation in copper (Ref 4, 5).

Lower-conductivity alloys, which are strengthened by alloy additions or precipitation hardening, exhibit improved resistance to stress relaxation, compared to pure copper. Figure 5 gives stress-relaxation data for a precipitation-hardened beryllium copper alloy (C17200). The performance of any particular material will be dependent on the chemical composition, condition, and temperature at which it is tested. For materials that are strengthened by cold rolling, several general comments can be made. First, the amount of relaxation that will occur during a given time at a certain temperature will increase with increasing amounts of prior cold work. Second, the performance of these materials can vary depending on the orientation of the test sample to the rolling direction. Finally, the performance of heavily cold-rolled materials can be improved by stress-relief annealing (Ref 6 and 7). Figure 6 illustrates these effects for copper alloyed with 5% Sn (C51000).

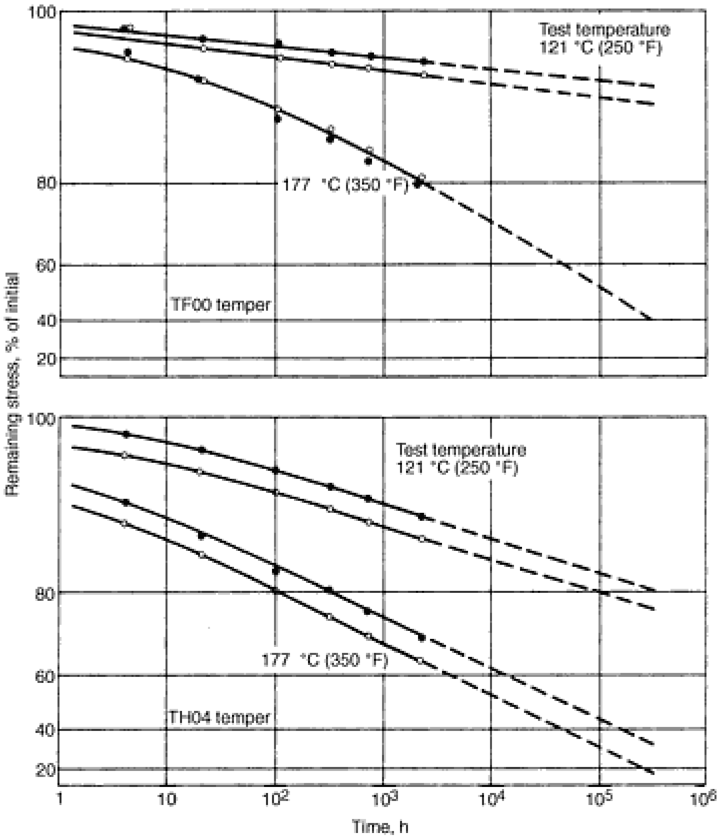


Fig. 5 Stress relaxation in C17200 at two levels of initial stress. Data are for beryllium copper (1.9% Be) strip, 0.38 mm (0.015 in.) thick. Open symbols represent initial test stress equal to 80% of the monotonic bending yield stress; solid symbols represent initial stress 50% of the bending yield stress. This alloy has adequate resistance to stress relaxation at temperatures up to 120 °C (250 °F), provided the initial stress is below the elastic limit.

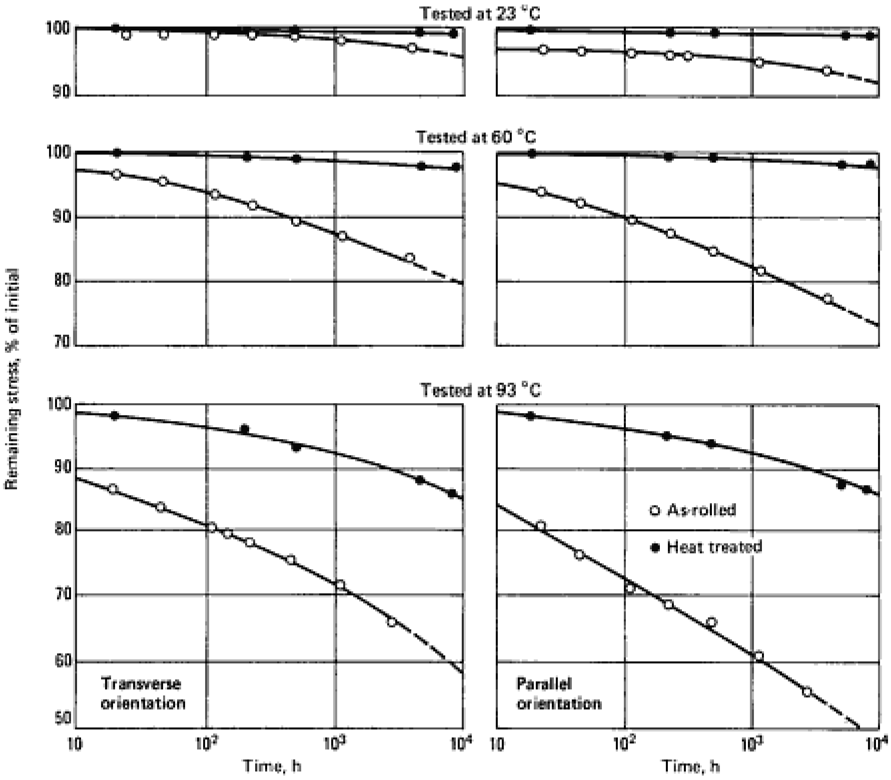


Fig. 6 Anisotropic stress-relaxation behavior in bending for highly cold-worked C51000 strip. Data are for 5% Sn phosphor bronze cold rolled 93% (reduction in area) to 0.25 mm (0.01 in.) and heat treated 2 h at 260 °C (500 °F). Graphs at left are for stress relaxation transverse to the rolling direction; graphs at right, for stress relaxation parallel to the rolling direction. Initial stresses: as rolled, parallel orientation, 607 MPa (88 ksi); as rolled, transverse orientation, 634 MPa (92 ksi); heat treated, parallel orientation, 641 MPa (93 ksi); heat treated, transverse orientation, 738 MPa (107 ksi)

Table 2 provides bending stress-relaxation data at 75 °C (165 °F) for solid-solution and dispersion hardened copper alloys commonly used in electrical and electronic spring applications. Tensile strength and electrical conductivity values also are tabulated. In general, the resistance to stress relaxation, as measured by percentage of stress remaining, increases with solute hardening additions but with some sacrifice in electrical conductivity. It should be noted that stress relaxation resistance can be expected to decrease with increasing tensile strength (temper) for a given alloy.

Table 2 Bending-stress-relaxation data at 75 °C for commonly used electronic spring materials

Alloy	Conductivity, % IACS	Tensile strength		Stress remaining[(a)], %	
		MPa	**ksi**	**1000 h**	**10^5 h**
C15100	90	434	63	81	74
C19400	65	448	65	88	83
C19500	50	586	85	79	72

C26000	28	565	82	74	63
C42500	28	565	82	87	80
C51000	15	483	70	92	86
C65400	7	779	113	87	80
C68800	18	800	116	82	73
C72500	11	613	89	90	87
C75200	9	620	90	93	90

(a) The values for percentage of stress remaining at 10^5 h are extrapolated from 1000 h test data. Initial stress level was ~80% of the 0.2% offset yield stress.

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Corrosion Characteristics of Copper and Copper Alloys

Introduction

COPPER AND COPPER ALLOYS are widely used in many environments and applications because of their excellent corrosion resistance, which is coupled with combinations of other desirable properties, such as superior electrical and thermal conductivity, ease of fabricating and joining, wide range of attainable mechanical properties, and resistance to biofouling. Copper corrodes at negligible rates in unpolluted air, water, and deaerated nonoxidizing acids. Copper alloy artifacts have been found in nearly pristine condition after having been buried in the earth for thousands of years, and copper roofing in rural atmospheres has been found to corrode at rates of less than 0.4 mm (15 mils) in 200 years. Copper alloys resist many saline solutions, alkaline solutions, and organic chemicals. However, copper is susceptible to more rapid attack in oxidizing acids, oxidizing heavy-metal salts, sulfur, ammonia (NH_3), and some sulfur and NH_3 compounds. Resistance to acid solution depends mainly on the severity of oxidizing conditions in the solution. Reaction of copper with sulfur and sulfides to form copper sulfide (CuS or Cu_2S) usually precludes the use of copper and copper alloys in environments known to contain certain sulfur species.

Copper and copper alloys provide superior service in many of the applications included in the following general classifications:

- Applications requiring resistance to atmospheric exposure, such as roofing and other architectural uses, hardware, building fronts, grille work, hand rails, lock bodies, doorknobs, and kick plates
- Freshwater supply lines and plumbing fittings, for which superior resistance to corrosion by various types of waters and soils is important
- Marine applications--most often freshwater and seawater supply lines, heat exchangers, condensers, shafting, valve stems, and marine hardware--in which resistance to seawater, hydrated salt deposits, and biofouling from marine organisms is important
- Heat exchangers and condensers in marine service, steam power plants, and chemical process applications, as well as liquid-to-gas or gas-to-gas heat exchangers in which either process stream may contain a corrosive contaminant
- Industrial and chemical plant process equipment involving exposure to a wide variety of organic and inorganic chemicals
- Electrical wiring, hardware, and connectors; printed circuit boards; and electronic applications that require demanding combinations of electrical, thermal, and mechanical properties, such as semiconductor packages, lead frames, and connectors

Forms of Corrosion

Coppers and copper alloys, like most other metals and alloys, are susceptible to several forms of corrosion, depending primarily on environmental conditions. Table 1 lists the identifying characteristics of the forms of corrosion that commonly attack copper metals as well as the most effective means of combating each.

Table 1 Guide to corrosion of copper alloys

Form of attack	Characteristics	Preventive measures
General thinning	Uniform metal removal	Select proper alloy for environmental conditions based on weight loss data
Galvanic corrosion	Corrosion preferentially near a more cathodic metal	Avoid electrically coupling dissimilar metals; maintain optimum ratio of anode to cathode area; maintain optimum concentration of oxidizing constituent in corroding medium
Pitting	Localized pits, tubercles; water line pitting; crevice corrosion; pitting under foreign objects or dirt	Alloy selection; design to avoid crevices; keep metal clean
Impingement: erosion-corrosion cavitation	Erosion attack from turbulent flow plus dissolved gases, generally as lines of pits in direction of fluid flow	Design for streamlined flow; keep velocity low; remove gases from liquid phase; use erosion-resistant alloy

Fretting	Chafing or galling, often occurring during shipment	Lubricate contacting surfaces; interleave sheets of paper between sheets of metal; decrease load on bearing surfaces
Intergranular corrosion	Corrosion along grain boundaries without visible signs of cracking	Select proper alloy for environmental conditions based on metallographic examination of corrosion specimens
Dealloying	Preferential dissolution of zinc or nickel, resulting in a layer of sponge copper	Select proper alloy for environmental conditions based on metallographic examination of corrosion specimens
Corrosion fatigue	Several transgranular cracks	Select proper alloy based on fatigue tests in service environment; reduce mean or alternating stress
Stress-corrosion cracking (SCC)	Cracking, usually intergranular but sometimes transgranular, that is often fairly rapid	Select proper alloy based on stress-corrosion tests; reduce applied or residual stress; remove mercury compounds or NH_3 from environment

General Corrosion

General corrosion is the well-distributed attack of an entire surface with little or no localized penetration. It is the least damaging of all forms of attack. General corrosion is the only form of corrosion for which weight loss data can be used to estimate penetration rates accurately.

General corrosion of copper alloys results from prolonged contact with environments in which the corrosion rate is very low, such as fresh, brackish, and salt water; many types of soil; neutral, alkaline, and acid salt solutions, organic acids; and sugar juices. Other substances that cause uniform thinning at a faster rate include oxidizing acids, sulfur-bearing compounds, NH_3, and cyanides.

Galvanic Corrosion

An electrochemical potential almost always exists between two dissimilar metals when they are immersed in a conductive solution. If two dissimilar metals are in electrical contact with each other and immersed in a conductive solution, a potential results that enhances the corrosion of the more electronegative member of the couple (the anode) and partly or completely protects the more electropositive member (the cathode). Copper metals are almost always cathodic to other common structural metals, such as steel and aluminum. When steel or aluminum is put in contact with a copper metal, the corrosion rate of the steel or aluminum increases, but that of the copper metal decreases. The common grades of stainless steel exhibit variable behavior; that is, copper metals may be anodic or cathodic to the stainless steel, depending on conditions of exposure. Copper metals usually corrode preferentially when coupled with high-nickel alloys, titanium, or graphite.

Corrosion potentials of copper metals generally range from -0.2 to -0.4 V when measured against a saturated calomel electrode (SCE); the potential of pure copper is about -0.3 V. Alloying additions of zinc or aluminum move the potential toward the anodic (more electronegative) end of the range; additions of tin or nickel move the potential toward the cathodic (less electronegative) end. Galvanic corrosion between two copper metals is seldom a significant problem, because the potential difference is so small.

Table 2 lists a galvanic series of metals and alloys valid for dilute aqueous solutions, such as seawater and weak acids. The metals that are grouped together can be coupled to each other without significant galvanic damage. However, the connecting of metals from different groups leads to damage of the more anodic metal; the larger the difference in galvanic potential between groups, the greater the corrosion. Accelerated damage due to galvanic effects is usually greatest near the junction, where the electrochemical current density is the highest.

Table 2 Galvanic series in seawater

Anodic end
Magnesium
Magnesium alloys
Zinc
Galvanized steel
Aluminum alloy 5052H
Aluminum alloy 3004
Aluminum alloy 3003
Aluminum alloy 1100
Aluminum alloy 6053
Alclad aluminum alloys
Cadmium
Aluminum alloy 2017
Aluminum alloy 2024
Low-carbon steel
Wrought iron
Cast iron
Ni-resist cast iron
AISI type 410 stainless steel (active)
50Pb-50Sn solder

AISI type 304 stainless steel (active)
AISI type 316 stainless steel (active)
Lead
Tin
Muntz metal (C28000)
Manganese bronze (C67500)
Naval brass (C46400)
Nickel (active)
Inconel (active)
Cartridge brass (C26000)
Admiralty metal (C44300)
Aluminum bronze (C61400)
Red brass (C23000)
Copper (C11000)
Silicon bronze (C65100)
Copper nickel, 30% (C71500)
Nickel (passive)
Inconel (passive)
Monel
AISI type 304 stainless steel (passive)
AISI type 316 stainless steel (passive)

Silver
Gold
Platinum
Cathodic end

Another factor that affects galvanic corrosion is area ratio. An unfavorable area ratio exists when the cathodic area is large and the anodic area is small. The corrosion rate of the small anodic area may be several hundred times greater than if the anodic and cathodic areas were equal in size. Conversely, when a large anodic area is coupled to a small cathodic area, current density and damage due to galvanic corrosion are much less. For example, copper rivets (cathodic) used to fasten steel plates together lasted longer than 1.5 years in seawater, but steel rivets used to fasten copper plates were completely destroyed during the same period.

Five principal methods are available for eliminating or significantly reducing galvanic corrosion:

- Select dissimilar metals that are as close as possible to each other in the galvanic series
- Avoid coupling small anodes to large cathodes
- Insulate dissimilar metals completely wherever practicable
- Apply coatings and keep them in good repair, particularly on the cathodic member
- Use a sacrificial anode; that is, couple the system to a third metal that is anodic to both structural metals

Pitting

As with most commercial metals, corrosion of copper metals results in pitting under certain conditions. Pitting is sometimes general over the entire surface, giving the metal an irregular and roughened appearance. In other cases, pits are concentrated in specific areas and are of various sizes and shapes.

Localized pitting is the most damaging form of corrosive attack because it reduces load-carrying capacity and increases stress concentration by creating depressions or holes in the metal. Pitting is the usual form of corrosive attack at surfaces on which there are incomplete protective films, nonprotective deposits of scale, or extraneous deposits of dirt or other foreign substances.

In seawater, pitting tends to occur more often under conditions of relatively low water velocity, typically less than 0.6 to 0.9 m/s (2 to 3 ft/s). The occurrence of pitting is somewhat random regarding the specific location of a pit on the surface as well as whether it will even occur on a particular metal sample. Long-term tests of copper alloys show that the average pit depth does not continually increase with extended times of exposure. Instead, pits tend to reach a certain limit beyond which little apparent increase in depth occurs. Of the copper alloys, the most pit resistant are the aluminum bronzes with less than 8% Al and the low-zinc brasses. Copper nickels and tin bronzes tend to have intermediate pitting resistance, but the high-copper alloys and silicon bronzes are somewhat more prone to pitting.

Crevice corrosion is a form of localized corrosion that occurs near a crevice formed either by two metal surfaces or a metal and a nonmetal surface. Like pitting, crevice attack is a random occurrence, the precise location of which cannot always be predicted. Also, like pitting, the depth of attack appears to level off rather than to increase continually with time. This depth is usually less than that from pitting, and for most copper alloys, it will be less than 400 μm (15.8 mils).

For most copper alloys, the location of the attack will be outside but immediately adjacent to the crevice due to the formation of metal ion concentration cells. Classic crevice corrosion resulting from oxygen depletion and attack within crevices is less common in copper alloys. Aluminum- and chromium-bearing copper alloys, which form more passive surface films, are susceptible to differential oxygen cell attack, as are aluminum alloys and stainless steels.

Local cell action similar to crevice attack can also result from the presence of foreign objects or debris, such as dirt, pieces of shell, or vegetation, or it may result from rust, permeable scales, or uneven accumulation of corrosion product on the metallic surface. This type of attack can sometimes be controlled by cleaning the surfaces. For example, condensers and heat exchangers are cleaned periodically to prevent deposit attack.

Water line attack is a term used to describe pitting due to a differential oxygen cell functioning between the well-aerated surface layer of a liquid and the oxygen-starved layer immediately beneath it. The pitting occurs immediately below the water line.

Impingement

Various forms of impingement attack occur where gases, vapors, or liquids impinge on metal surfaces at high velocities, such as in condensers or heat exchangers. Rapidly moving turbulent water can strip away the protective films from copper alloys. When this occurs, the metal corrodes at a more rapid rate in an attempt to reestablish this film, but because the films are being swept away as rapidly as they are being formed, the corrosion rate remains constant and high.

Erosion-corrosion is characterized by undercut grooves, waves, ruts, gullies, and rounded holes; it usually exhibits a directional pattern. Pits are elongated in the direction of flow and are undercut on the downstream side. When the corrosion becomes severe, it may result in a pattern of horseshoe-shaped grooves or pits with their open ends pointing downstream. As attack progresses, the pits may join, forming fairly large patches of undercut pits. When this form of corrosion occurs in a condenser tube, it is usually confined to a region near the inlet end of the tube where fluid flow is rapid and turbulent. If some of the tubes in a bundle become plugged, the velocity is increased in the remaining tubes; therefore, the unit should be kept as clean as possible. Erosion-corrosion is most often found with waters containing low levels of sulfur compounds and with polluted, contaminated, or silty salt water or brackish water. The erosive action locally removes protective films, thus contributing to the formation of concentration cells and to localized pitting of anodic sites.

Cavitation is a phenomenon that occurs in moving water when the flow is disturbed so as to create a local pressure drop. Under these conditions, a vapor bubble will form and then collapse, applying a momentary stress of up to 1379 MPa (200 ksi) to the surface. This repeated mechanical working of the surface creates a local fatigue situation that aids the removal of the metal. The harder alloys tend to have greater resistance to cavitation and there is often an incubation period before the onset of cavitation attack. Of the copper alloys, aluminum bronze has the best cavitation resistance.

Impingement attack can be reduced, and the life of the unit extended, by decreasing fluid velocity, streamlining the flow, and removing entrained air. This is usually accomplished by redesigning water boxes, injector nozzles, and piping to reduce or eliminate low-pressure pockets, obstructions to smooth flow, abrupt changes in flow direction, and other features that cause local regions of high-velocity or turbulent flow. Condensers and heat exchangers are less susceptible to impingement attack if they are made of one of the aluminum brasses or copper nickels, which are more erosion resistant than the brasses or tin brasses. Erosion-resistant inserts at tube inlets and epoxy-type coatings are often effective repair methods in existing shell and tube heat exchangers. When contaminated waters are involved, filtering or screening the liquids and cleaning the surfaces can be very effective in minimizing impingement attack. The use of cathodic protection can lessen all forms of localized attack except cavitation.

Fretting

Another form of attack, called fretting or fretting corrosion, appears as pits or grooves in the metal surface that are surrounded or filled with corrosion product. Fretting is sometimes referred to as chafing, road burn, friction oxidation, wear oxidation, or galling.

The basic requirements for fretting are as follows:

- Repeated relative (sliding) motion between two surfaces must occur. The relative amplitude of the motion may be very small--motion of only a few tenths of a millimeter is typical
- The interface must be under load
- Both load and relative motion must be sufficient to produce deformation of the interface
- Oxygen and/or moisture must be present

Fretting does not occur on lubricated surfaces in continuous motion, such as axle bearings, but instead on dry interfaces subject to repeated, small relative displacements. A classic type of fretting occurs during shipment of bundles of mill products having flat faces. Fretting is not confined to coppers and copper alloys, but has been recognized on almost every kind of surface--steel, aluminum, noble metals, mica, and glass.

Fretting can be controlled, and sometimes eliminated, by:

- Lubricating with low-viscosity high-tenacity oils to reduce friction at the interface between the two metals and to exclude oxygen from the interface
- Separating the faying surfaces by interleaving an insulating material
- Increasing the load to reduce motion between faying surfaces; this may be difficult in practice, because only a minute amount of relative motion is necessary to produce fretting
- Decreasing the load at bearing surfaces to increase the relative motion between parts

Intergranular Corrosion

Intergranular corrosion is an infrequently encountered form of attack that occurs most often in applications involving high-pressure steam. This type of corrosion penetrates the metal along grain boundaries--often to a depth of several grains--which distinguishes it from surface roughening. Mechanical stress is apparently not a factor in intergranular corrosion. The alloys that appear to be the most susceptible to this form of attack are Muntz metal, admiralty metal, aluminum brasses, and silicon bronzes.

Dealloying

Dealloying is a corrosion process in which the more active metal is selectively removed from an alloy, leaving behind a weak deposit of the more noble metal. Copper-zinc alloys containing more than 15% Zn are susceptible to a dealloying process called dezincification. In the dezincification of brass, selective removal of zinc leaves a relatively porous and weak layer of copper and copper oxide. Corrosion of a similar nature continues beneath the primary corrosion layer, resulting in gradual replacement of sound brass by weak, porous copper. Unless arrested, dealloying eventually penetrates the metal, weakening it structurally and allowing liquids or gases to leak through the porous mass in the remaining structure.

The term *plug-type dealloying* refers to the dealloying that occurs in local areas; surrounding areas are usually unaffected or only slightly corroded (Fig. 1). In *uniform-layer dealloying*, the active component of the alloy is leached out over a broad area of the surface (Fig. 2). Dezincification is the usual form of corrosion for uninhibited brasses in prolonged contact with waters high in oxygen and carbon dioxide, CO_2. It is frequently encountered with quiescent or slowly moving solutions. Slightly acidic water, low in salt content and at room temperature, is likely to produce uniform attack, but neutral or alkaline water, high in salt content and above room temperature, often produces plug-type attack.

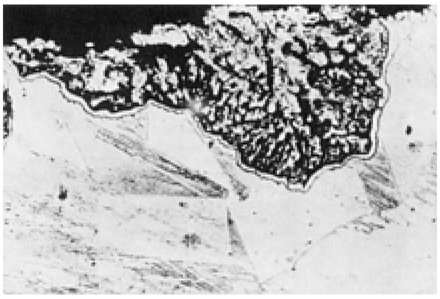

Fig. 1 Plug-type dezincification in an α-brass (70Cu-30Zn) exposed for 79 days in 1 *N* NaCl at room temperature. Note porous structure within the plug. The dark line surrounding the plug is an etching artifact. 160×

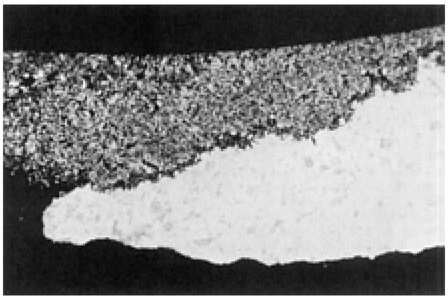

Fig. 2 Uniform-layer dezincification in an admiralty brass heat-exchanger tube. The top layer of the micrograph, which consists of porous, disintegrated particles of copper, was from the inner surface of the tube that was exposed to water at pH 8.0, 31 to 49 °C (87 to 120 °F), and 207 kPa (30 psi). Below the dezincified layer is the bright yellow, intact, admiralty brass outer tube wall. 35×

Brasses with copper contents of 85% or more resist dezincification. Dezincification of brasses with two-phase structures is generally more severe, particularly if the second phase is continuous; it usually occurs in two stages: the high-zinc β phase, followed by the lower-zinc α phase.

Tin tends to inhibit dealloying, especially in cast alloys. Alloys C46400 (naval brass) and C67500 (manganese bronze) which are α-β brasses containing ~1% Sn, are widely used for naval equipment and have reasonably good resistance to dezincification. Addition of a small amount of phosphorus, arsenic, or antimony to admiralty metal (an all-α 71Cu-28Zn-1Sn brass) inhibits dezincification. Inhibitors are not entirely effective in preventing dezincification of the α-β brasses, because they do not prevent dezincification of the β phase.

Where dezincification is a problem, red brass, commercial bronze, inhibited admiralty metal, and inhibited aluminum brass can be successfully used. In some cases, the economic penalty of avoiding dealloying by selecting a low-zinc alloy may be unacceptable. Low-zinc alloy tubing requires fittings that are available only as sand castings, but fittings for high-zinc tube can be die cast or forged much more economically. Where selection of a low-zinc alloy is unacceptable, inhibited yellow brasses are generally preferred.

Dealloying has been observed in other alloys. Dealloying of aluminum occurs in some copper-aluminum alloys, particularly with those having more than 8% Al. It is especially severe in alloys with continuous γ phase and usually occurs as plug-type dealloying. Nickel additions exceeding 3.5% or heat treatment to produce an $\alpha + \beta$ microstructure prevents dealloying. Dealloying of nickel in C71500 is rare, having been observed at temperatures over 100 °C (212 °F), low flow conditions, and high local heat flux. Dealloying of tin in cast tin bronzes has been observed as a rare occurrence in hot brine or steam. Cathodic protection generally protects all but the two-phase, copper-zinc alloys from dealloying.

Corrosion Fatigue

The combined action of corrosion (usually pitting corrosion) and cyclic stress may result in corrosion fatigue cracking. Like ordinary fatigue cracks, corrosion fatigue cracks generally propagate at right angles to the maximum tensile stress in the affected region. However, cracks resulting from simultaneous fluctuating stress and corrosion propagate much more rapidly than cracks caused solely by fluctuating stress. Also, corrosion fatigue failure usually involves several parallel cracks, but it is rare for more than one crack to be found in a part that has failed by simple fatigue. The cracks shown in Fig. 3 are characteristic of service failures resulting from corrosion fatigue.

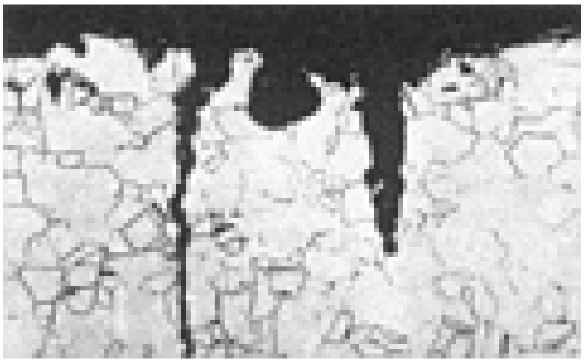

Fig. 3 Typical corrosion fatigue cracking of a copper alloy. Transgranular cracks originate at the base of corrosion pits on the roughened inner surface of a tube. Etched. Approximately 150×

Ordinarily, corrosion fatigue can be readily identified by the presence of several cracks emanating from corrosion pits. Cracks not visible to the unaided eye or at low magnification can be made visible by deep etching or plastic deformation or can be detected by eddy-current inspection. Corrosion fatigue cracking is often transgranular, but there is evidence that certain environments induce intergranular cracking in copper metals.

In addition to effective resistance to corrosion, copper and copper alloys also resist corrosion fatigue in many applications involving repeated stress and corrosion. These applications include such parts as springs, switches, diaphragms, bellows, aircraft and automotive gasoline and oil lines, tubes for condensers and heat exchangers, and fourdrinier wire for the paper industry.

Copper alloys that are high in fatigue limit and resistance to corrosion in the service environment are more likely to have good resistance to corrosion fatigue. Alloys frequently used in applications involving both cyclic stress and corrosion include beryllium coppers, phosphor bronzes, aluminum bronzes, and copper nickels.

Stress-Corrosion Cracking

Stress-corrosion cracking (SCC) and season cracking describe the same phenomenon--the apparently spontaneous cracking of stressed metal. Stress corrosion cracking is often intergranular (Fig. 4), but transgranular cracking may occur in some alloys in certain environments. Stress-corrosion cracking occurs only if a susceptible alloy is subjected to the combined effects of sustained stress and certain chemical substances.

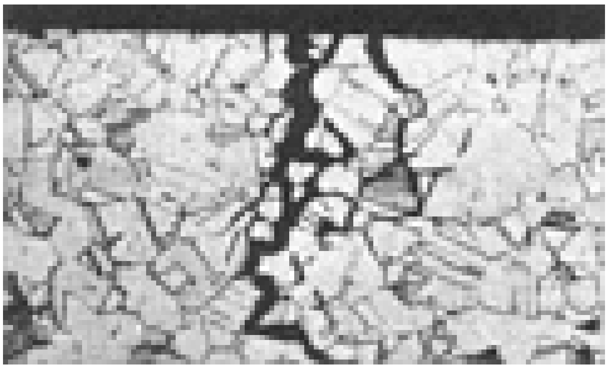

Fig. 4 Typical stress-corrosion cracking in a copper alloy. Intergranular cracking in an etched specimen. Approximately 60×

Conditions Leading to SCC. Ammonia and ammonium compounds are the corrosive substances most often associated with SCC of copper alloys. These compounds are sometimes present in the atmosphere; in other cases, they are in cleaning compounds or in chemicals used to treat boiler water. Both oxygen and moisture must be present for NH_3 to be corrosive to copper alloys; other compounds, such as CO_2 are thought to accelerate SCC in NH_3 atmospheres. Moisture films on metal surfaces will dissolve significant quantities of NH_3, even from atmospheres with low NH_3 concentrations.

A specific corrosive environment and sustained stress are the primary causes of SCC; microstructure and alloy composition may affect the rate of crack propagation in susceptible alloys. Microstructure and composition can be most effectively controlled by selecting the correct combination of alloy, forming process, thermal treatment, and metal-finishing process. Although test results may indicate that a finished part is not susceptible to SCC, such an indication does not ensure complete freedom from cracking, particularly where service stresses are high.

Applied and residual stresses can both lead to failure by SCC. Susceptibility is largely a function of stress magnitude. Stresses near the yield strength are usually required, but parts have failed under much lower stresses. In general, the higher the stress, the weaker the corroding medium must be to cause SCC. The reverse is also true; the stronger the corroding medium, the lower the required stress.

Sources of Stress. Applied stresses result from ordinary service loading or from fabricating techniques, such as riveting, bolting, shrink fitting, brazing, and welding. Residual stresses are of two types: differential-strain stresses, which result from nonuniform plastic strain during cold forming, and differential-thermal-contraction stresses, which result from nonuniform heating and/or cooling.

Residual stresses induced by nonuniform straining are primarily influenced by the method of fabrication. In some fabricating processes, it is possible to cold work a metal extensively and yet produce only a low level of residual stress. For example, residual stress in a drawn tube is influenced by die angle and amount of reduction. Wide-angle dies (about 32°) produce higher residual stresses than narrow-angle dies (about 8°). Light reductions yield high residual stresses because only the surface of the alloy is stressed; heavy reductions yield low residual stresses because the region of cold working extends deeper into the metal. Most drawing operations can be planned so that residual stresses are low and susceptibility to SCC is negligible.

Residual stresses resulting from upsetting, stretching, or spinning are more difficult to evaluate and to control by varying tooling and process conditions. For these operations, SCC can be prevented more effectively by selecting a resistant alloy or by treating the metal after fabrication.

Alloy Composition. Brasses containing less than 15% Zn are highly resistant to SCC. Phosphorus-deoxidized copper and tough pitch copper rarely exhibit SCC, even under severe conditions. On the other hand, brasses containing 20 to 40% Zn are highly susceptible. Susceptibility increases only slightly as zinc content is increased from 20 to 40%.

There is no indication that the other elements commonly added to brasses increase the probability of SCC. Phosphorus, arsenic, magnesium, tellurium, tin, beryllium, and manganese are thought to decrease susceptibility under some conditions. Addition of 1.5% Si is known to decrease the probability of cracking.

Altering the microstructure cannot make a susceptible alloy totally resistant to SCC. However, the rapidity with which susceptible alloys crack appears to be affected by grain size and structure. All other factors being equal, the rate of cracking increases with grain size. The effects of structure on SCC are not sharply defined, primarily because they are interrelated with effects of both composition and stress.

Control Measures. Stress-corrosion cracking can be controlled, and sometimes prevented, by selecting copper alloys that have high resistance to cracking (notably those with less than 15% Zn); by reducing residual stress to a safe level by thermal stress relief, which can usually be applied without significantly decreasing strength; or by altering the environment, such as by changing the predominant chemical species present or introducing a corrosion inhibitor.

Residual and assembly stresses can be eliminated by recrystallization annealing after forming or assembly. Recrystallization annealing cannot be used when the integrity of the structure depends on the higher strength of strain-hardened metal, which always contains a certain amount of residual stress. Thermal stress relief (sometimes called relief annealing) can be specified when the higher strength of a cold-worked temper must be retained. Thermal stress relief consists of heating the part for a relatively short time at low temperature. Specific times and temperatures depend on alloy composition, severity of deformation, prevailing stresses, and the size of the load being heated. Usually, time is from 30 min to 1 h and temperature is from 150 to 425 °C (300 to 795 °F). Table 3 lists typical stress-relieving times and temperatures for some of the more common copper alloys.

Table 3 Typical stress-relieving parameters for some common copper alloys

Common name	UNS No.	Temperature		Time, h
		°C	°F	
Commercial bronze	C22000	205	400	1
Cartridge brass	C26000	260	500	1
Muntz metal	C28000	190	375	$\frac{1}{2}$
Admiralty metal	C44300, C44400, C44500	300	575	1
Phosphor bronze, 5 or 10%	C51000, C52400	190	375	1
Silicon bronze	C65500	370	700	1
Aluminum bronze	C61300, C61400	400	750	1
Copper nickel, 30%	C71500	425	800	1

The exact thermal treatment should be established by examining specific parts for residual stress. If such examination indicates that a thermal treatment is insufficient, temperature and/or time should be adjusted until satisfactory results are obtained. Parts in the center of a furnace load may not reach the desired temperature as soon as parts around the periphery. Therefore, it may be necessary to compensate for furnace loading when setting process controls or to limit the number of parts that can be stress relieved together.

Mechanical methods, such as stretching, flexing, bending, straightening between rollers, peening, and shot blasting, can also be used to reduce residual stresses to a safe level. These methods depend on plastic deformation to decrease dangerous tensile stresses or to convert them to less objectionable compressive stresses.

Effects of Alloy Compositions

Coppers and high-copper alloys have similar corrosion resistance. They have excellent resistance to seawater corrosion and biofouling, but are susceptible to erosion-corrosion at high water velocities. The high-copper alloys are primarily used in applications that require enhanced mechanical performance, often at slightly elevated temperature, with good thermal or electrical conductivity. Processing for increased strength in the high-copper alloys generally improves their resistance to erosion-corrosion. A number of alloys in this category have been developed for electronic applications--such as contact clips, springs, and lead frames--that require specific mechanical properties, relatively high electrical conductivity, and atmospheric-corrosion resistance.

Brasses are basically copper-zinc alloys and are the most widely used group of copper alloys. The resistance of brasses to corrosion by aqueous solutions does not change markedly as long as the zinc content does not exceed ~15%; above 15% Zn, dezincification may occur. Quiescent or slowly moving saline solutions, brackish waters, and mildly acidic solutions are environments that often lead to the dezincification of unmodified brasses.

Susceptibility to SCC is significantly affected by zinc content; alloys that contain more zinc are more susceptible. Resistance increases substantially as zinc content decreases from 15 to 0%. Stress-corrosion cracking is practically unknown in commercial copper.

Elements such as lead, tellurium, beryllium, chromium, phosphorus, and manganese have little or no effect on the corrosion resistance of coppers and binary copper-zinc alloys. These elements are added to enhance such mechanical properties as machinability, strength, and hardness.

Tin Brasses. Tin additions significantly increase the corrosion resistance of some brasses, especially resistance to dezincification. Examples of this effect are two tin-bearing brasses, especially resistance to dezincification. Examples of this effect are two tin-bearing brasses: uninhibited admiralty metal (no active UNS number) and naval brass (C46400). Uninhibited admiralty metal was once widely used to make heat-exchanger tubes; it has largely been replaced by inhibited grades of admiralty metal (C44300, C44400, and C44500), which have even greater resistance to dealloying. Admiralty metal is a variation of cartridge brass (C26000) that is produced by adding ~1% Sn to the basic 70Cu-30Zn composition. Similarly, naval brass is the alloy resulting from the addition of 0.75% Sn to the basic 60Cu-40Zn composition of Muntz metal (C28000).

Aluminum Brasses. An important constituent of the corrosion film on a brass that contains a few percent aluminum in addition to copper and zinc is aluminum oxide (Al_2O_3), which markedly increases resistance to impingement attack in turbulent high-velocity saline water. For example, the arsenical aluminum brass C68700 (76Cu-22Zn-2Al) is frequently used for marine condensers and heat exchangers in which impingement attack is likely to pose a serious problem. Aluminum brasses are susceptible to dezincification unless they are inhibited, which is usually done by adding 0.02 to 0.10% As.

Inhibited Alloys. Addition of phosphorus, arsenic, or antimony (typically 0.02 to 0.10%) to admiralty metal, naval brass, or aluminum brass effectively produces high resistance to dezincification. Inhibited alloys have been extensively used for such components as condenser tubes, which must accumulate years of continuous service between shutdowns for repair or replacement.

Phosphor Bronzes. Addition of tin and phosphorus to copper produces good resistance to flowing seawater and to most nonoxidizing acids except hydrochloric (HCl). Alloys containing 8 to 10% Sn have high resistance to impingement attack. Phosphor bronzes are much less susceptible to SCC than brasses and are similar to copper in resistance to sulfur attack.

Tin bronzes, which are used primarily in cast form, are modified by further alloy additions of lead, zinc, and nickel. This group of alloys has fair resistance to impingement and good resistance to biofouling.

Copper Nickels. Alloy C71500 (Cu-30Ni) has the best general resistance to aqueous corrosion of all the commercially important copper alloys, but C70600 (Cu-10Ni) is often selected because it offers good resistance at lower cost. Both of these alloys, although well suited to applications in the chemical industry, have been most extensively used for condenser tubes and heat-exchanger tubes in recirculating steam systems. They are superior to coppers and to other copper alloys in resisting acid solutions and are highly resistant to SCC and impingement corrosion.

Nickel Silvers. The two most common nickel silvers are C75200 (65Cu-18Ni-17Zn) and C77000 (55Cu-18Ni-27Zn). They have good resistance to corrosion in both fresh and salt waters. Primarily because their relatively high nickel contents inhibit dezincification, C75200 and C77000 are usually much more resistant to corrosion in saline solutions than brasses of similar copper content.

Copper-silicon alloys generally have the same corrosion resistance as copper, but they have higher mechanical properties and superior weldability. These alloys appear to be much more resistant to SCC than the common brasses. Silicon bronzes are susceptible to embrittlement by high-pressure steam and should be tested for suitability in the service environment before being specified for components to be used at elevated temperature.

Aluminum bronzes containing 5 to 12% Al have excellent resistance to impingement corrosion and high-temperature oxidation. Aluminum bronzes are used for beater bars and for blades in wood pulp machines because of their ability to withstand mechanical abrasion and chemical attack by sulfite solutions.

In most practical commercial applications, the corrosion characteristics of aluminum bronzes are primarily related to aluminum content. Alloys with up to 8% Al normally have completely face-centered cubic (fcc) α structures and good resistance to corrosion attack. As aluminum content increases above 8%, α-β duplex structures appear. The β phase is a high-temperature phase retained at room temperature upon fast cooling from 565 °C (1050 °F) or above. Slow cooling for long exposure at temperatures from 320 to 565 °C (610 to 1050 °F) tends to decompose the β phase into a brittle $\alpha + \gamma_2$ eutectoid having either a lamellar or a nodular structure. The β phase is less resistant to corrosion than the α phase, and eutectoid structures are even more susceptible to attack.

Depending on specific environmental conditions, β phase or eutectoid structure in aluminum bronze can be selectively attacked by a mechanism similar to the dezincification of brasses. Proper quench-and-temper treatment of duplex alloys, such as C62400 and C95400, produces a tempered β structure with reprecipitated acicular α crystals, a combination that is often superior in corrosion resistance to the normal annealed structures.

Iron-rich particles are distributed as small round or rosette particles throughout the structures of aluminum bronzes containing more than about 0.5% Fe. These particles sometimes impart a rusty tinge to the surface, but have no known effect on corrosion rates.

Nickel-aluminum bronzes are more complex in structure with the introduction of the κ phase. Nickel appears to alter the corrosion characteristics of the β phase to provide greater resistance to dealloying and cavitation erosion in most liquids. For C63200 and perhaps C95800, quench-and-temper treatments may yield even greater resistance to dealloying. Alloy C95700, a high-manganese cast aluminum bronze, is somewhat inferior in corrosion resistance to C95500 and C95800, which are low in manganese and slightly higher in aluminum.

Aluminum bronzes are generally suitable for service in nonoxidizing mineral acids, such as phosphoric (H_3PO_4), sulfuric (H_2SO_4), and HCl; organic acids, such as lactic, acetic (CH_3COOH), or oxalic; neutral saline solutions, such as sodium chloride (NaCl) or potassium chloride (KCl); alkalies, such as sodium hydroxide (NaOH), potassium hydroxide (KOH), and anhydrous ammonium hydroxide (NH_4OH); and various natural waters including sea, brackish, and potable waters. Environments to be avoided include nitric acid (HNO_3); some metallic salts, such as ferric chloride ($FeCl_3$) and chromic acid (H_2CrO_4); moist chlorinated hydrocarbons; and moist NH_3. Aeration can result in accelerated corrosion in many media that appear to be compatible.

Exposure under high tensile stress to moist NH_3 can result in SCC. In certain environments, corrosion can lower the fatigue limit to 25 to 50% of the normal atmospheric value.

Selection for Specific Environments

Selection of a suitably resistant material requires consideration of the many factors that influence corrosion including stress, velocity, galvanic coupling, concentration cells, initial surface conditions, and contamination of the surrounding medium. Over the years, experience has been the best criterion for selecting the most suitable alloy for a given environment. The Copper Development Association (CDA) has compiled much field experience in the form of the ratings shown in Table 4. The table should be used only as a guide; small changes in the environmental conditions sometimes degrade the performance of a given alloy from "suitable" to "not suitable."

Table 4 Corrosion ratings of wrought copper alloys in various corrosive media

This table is intended to serve only as a general guide to the behavior of copper and copper alloys in corrosive environments. It is impossible to cover in a simple tabulation the performance of a material for all possible variations of temperature, concentration, velocity, impurity content, degree of aeration, and stress. The ratings are based on general performance; they should be used with caution, and then only for the purpose of screening candidate alloys. The letters E, G, F, and P have the following significance: E, excellent: resists corrosion under almost all conditions of service. G, good: some corrosion will take place, but satisfactory service can be expected under all but the most severe conditions. F, fair: corrosion rates are higher than for the G classification, but the metal can be used if needed for a property other than corrosion resistance and if either the amount of corrosion does not cause excessive maintenance expense or the effects of corrosion can be lessened, such as by use of coatings or inhibitors. P, poor: corrosion rates are high, and service is generally unsatisfactory.

Corrosive medium	Coppers	Low-zinc brasses	High-zinc brasses	Special brasses	Phosphor bronzes	Aluminum bronzes	Silicon bronzes	Copper nickels	Nickel silvers
Acetate solvents	E	E	G	E	E	E	E	E	E
Acetic acid[(a)]	E	E	P	P	E	E	E	E	G
Acetone	E	E	E	E	E	E	E	E	E
Acetylene[(b)]	P	P	[(b)]	P	P	P	P	P	P
Alcohols[(a)]	E	E	E	E	E	E	E	E	E
Aldehydes	E	E	F	F	E	E	E	E	E
Alkylamines	G	G	G	G	G	G	G	G	G
Alumina	E	E	E	E	E	E	E	E	E
Aluminum chloride	G	G	P	P	G	G	G	G	G
Aluminum hydroxide	E	E	E	E	E	E	E	E	E
Aluminum sulfate and alum	G	G	P	G	G	G	G	E	G
Ammonia, dry	E	E	E	E	E	E	E	E	E
Ammonia, moist[(c)]	P	P	P	P	P	P	P	F	P
Ammonium chloride[(c)]	P	P	P	P	P	P	P	F	P
Ammonium hydroxide[(c)]	P	P	P	P	P	P	P	F	P
Ammonium nitrate[(c)]	P	P	P	P	P	P	P	F	P
Ammonium sulfate[(c)]	F	F	P	P	F	F	F	G	F
Aniline and aniline	F	F	F	F	F	F	F	F	F

dyes									
Asphalt	E	E	E	E	E	E	E	E	E
Atmosphere:									
Industrial[(c)]	E	E	E	E	E	E	E	E	E
Marine	E	E	E	E	E	E	E	E	E
Rural	E	E	E	E	E	E	E	E	E
Barium carbonate	E	E	E	E	E	E	E	E	E
Barium chloride	G	G	F	F	G	G	G	G	G
Barium hydroxide	E	E	G	E	E	E	E	E	E
Barium sulfate	E	E	E	E	E	E	E	E	E
Beer[(a)]	E	E	G	E	E	E	E	E	E
Beet-sugar syrup[(a)]	E	E	G	E	E	E	E	E	E
Benzene, benzine, benzol	E	E	E	E	E	E	E	E	E
Benzoic acid	E	E	E	E	E	E	E	E	E
Black liquor, sulfate process	P	P	P	P	P	P	P	G	P
Bleaching powder (wet)	G	G	P	G	G	G	G	G	G
Borax	E	E	E	E	E	E	E	E	E
Bordeaux mixture	E	E	G	E	E	E	E	E	E
Boric acid	E	E	G	E	E	E	E	E	E

Brines	G	G	P	G	G	G	G	E	E
Bromine, dry	E	E	E	E	E	E	E	E	E
Bromine, moist	G	G	P	F	G	G	G	G	G
Butane(d)	E	E	E	E	E	E	E	E	E
Calcium bisulfate	G	G	P	G	G	G	G	G	G
Calcium chloride	G	G	F	G	G	G	G	G	G
Calcium hydroxide	E	E	G	E	E	E	E	E	E
Calcium hypochlorite	G	G	P	G	G	G	G	G	G
Cane-sugar syrup(a)	E	E	E	E	E	E	E	E	E
Carbolic acid (phenol)	F	G	P	G	G	G	G	G	G
Carbonated beverages(a)(e)	E	E	E	E	E	E	E	E	E
Carbon dioxide, dry	E	E	E	E	E	E	E	E	E
Carbon dioxide, moist(a)(e)	E	E	E	E	E	E	E	E	E
Carbon tetrachloride, dry	E	E	E	E	E	E	E	E	E
Carbon tetrachloride, moist	G	G	F	G	E	E	E	E	E
Castor oil	E	E	E	E	E	E	E	E	E
Chlorine, dry(f)	E	E	E	E	E	E	E	E	E
Chlorine, moist	F	F	P	F	F	F	F	G	F
Chloracetic acid	G	F	P	F	G	G	G	G	G

Chloroform, dry	E	E	E	E	E	E	E	E	E
Chromic acid	P	P	P	P	P	P	P	P	P
Citric acid(a)	E	E	F	E	E	E	E	E	E
Copper chloride	F	F	P	F	F	F	F	F	F
Copper nitrate	F	F	P	F	F	F	F	F	F
Copper sulfate	G	G	P	G	G	G	G	E	G
Corn oil(a)	E	E	G	E	E	E	E	E	E
Cottonseed oil(a)	E	E	G	E	E	E	E	E	E
Creosote	E	E	G	E	E	E	E	E	E
Dowtherm "A"	E	E	E	E	E	E	E	E	E
Ethanol amine	G	G	G	G	G	G	G	G	G
Ethers	E	E	E	E	E	E	E	E	E
Ethyl acetate (esters)	E	E	G	E	E	E	E	E	E
Ethylene glycol	E	E	G	E	E	E	E	E	E
Ferric chloride	P	P	P	P	P	P	P	P	P
Ferric sulfate	P	P	P	P	P	P	P	P	P
Ferrous chloride	G	G	P	G	G	G	G	G	G
Ferrous sulfate	G	G	P	G	G	G	G	G	G
Formaldehyde (aldehydes)	E	E	G	E	E	E	E	E	E
Formic acid	G	G	P	F	G	G	G	G	G

Freon, dry	E	E	E	E	E	E	E	E	E
Freon, moist	E	E	E	E	E	E	E	E	E
Fuel oil, light	E	E	E	E	E	E	E	E	E
Fuel oil, heavy	E	E	G	E	E	E	E	E	E
Furfural	E	E	F	E	E	E	E	E	E
Gasoline	E	E	E	E	E	E	E	E	E
Gelatin(a)	E	E	E	E	E	E	E	E	E
Glucose(a)	E	E	E	E	E	E	E	E	E
Glue	E	E	G	E	E	E	E	E	E
Glycerin	E	E	G	E	E	E	E	E	E
Hydrobromic acid	F	F	P	F	F	F	F	F	F
Hydrocarbons	E	E	E	E	E	E	E	E	E
Hydrochloric acid (muriatic)	F	F	P	F	F	F	F	F	F
Hydrocyanic acid, dry	E	E	E	E	E	E	E	E	E
Hydrocyanic acid, moist	P	P	P	P	P	P	P	P	P
Hydrofluoric acid, anhydrous	G	G	P	G	G	G	G	G	G
Hydrofluoric acid, hydrated	F	F	P	F	F	F	F	F	F
Hydrofluosilicic acid	G	G	P	G	G	G	G	G	G
Hydrogen(d)	E	E	E	E	E	E	E	E	E

Hydrogen peroxide up to 10%	G	G	F	G	G	G	G	G	G
Hydrogen peroxide over 10%	P	P	P	P	P	P	P	P	P
Hydrogen sulfide, dry	E	E	E	E	E	E	E	E	E
Hydrogen sulfide, moist	P	P	F	F	P	P	P	F	F
Kerosene	E	E	E	E	E	E	E	E	E
Ketones	E	E	E	E	E	E	E	E	E
Lacquers	E	E	E	E	E	E	E	E	E
Lacquer thinners (solvents)	E	E	E	E	E	E	E	E	E
Latic acid(a)	E	E	E	E	E	E	E	E	E
Lime	E	E	E	E	E	E	E	E	E
Lime sulfur	P	P	F	F	P	P	P	F	F
Linseed oil	G	G	G	G	G	G	G	G	G
Lithium compounds	G	G	P	F	G	G	G	E	E
Magnesium chloride	G	G	F	F	G	G	G	G	G
Magnesium hydroxide	E	E	G	E	E	E	E	E	E
Magnesium sulfate	E	E	G	E	E	E	E	E	E
Mercury or mercury salts	P	P	P	P	P	P	P	P	P
Milk(a)	E	E	G	E	E	E	E	E	E

Molasses	E	E	G	E	E	E	E	E	E
Natural gas[(d)]	E	E	E	E	E	E	E	E	E
Nickel chloride	F	F	P	F	F	F	F	F	F
Nickel sulfate	F	F	P	F	F	F	F	F	F
Nitric acid	P	P	P	P	P	P	P	P	P
Oleic acid	G	G	F	G	G	G	G	G	G
Oxalic acid[(g)]	E	E	P	P	E	E	E	E	E
Oxygen[(h)]	E	E	E	E	E	E	E	E	E
Palmitic acid	G	G	F	G	G	G	G	G	G
Paraffin	E	E	E	E	E	E	E	E	E
Phosphoric acid	G	G	P	F	G	G	G	G	G
Picric acid	P	P	P	P	P	P	P	P	P
Potassium carbonate	E	G	E	E	E	E	E	E	E
Potassium chloride	G	G	P	F	G	G	G	E	E
Potassium cyanide	P	P	P	P	P	P	P	P	P
Potassium dichromate (acid)	P	P	P	P	P	P	P	P	P
Potassium hydroxide	G	G	F	G	G	G	G	E	E
Potassium sulfate	E	E	G	E	E	E	E	E	E
Propane[(d)]	E	E	E	E	E	E	E	E	E
Rosin	E	E	E	E	E	E	E	E	E

Seawater	G	G	F	E	G	E	G	E	E
Sewage	E	E	F	E	E	E	E	E	E
Silver salts	P	P	P	P	P	P	P	P	P
Soap solution	E	E	E	E	E	E	E	E	E
Sodium bicarbonate	E	E	G	E	E	E	E	E	E
Sodium bisulfate	G	G	F	G	G	G	G	E	E
Sodium carbonate	E	E	G	E	E	E	E	E	E
Sodium chloride	G	G	P	F	G	G	G	E	E
Sodium chromate	E	E	E	E	E	E	E	E	E
Sodium cyanide	P	P	P	P	P	P	P	P	P
Sodium dichromate (acid)	P	P	P	P	P	P	P	P	P
Sodium hydroxide	G	G	F	G	G	G	G	E	E,
Sodium hypochlorite	G	G	P	G	G	G	G	G	G
Sodium nitrate	G	G	P	F	G	G	G	E	E
Sodium peroxide	F	F	P	F	F	F	F	G	G
Sodium phosphate	E	E	G	E	E	E	E	E	E
Sodium silicate	E	E	G	E	E	E	E	E	E
Sodium sulfate	E	E	G	E	E	E	E	E	E
Sodium sulfide	P	P	F	F	P	P	P	F	F
Sodium thiosulfate	P	P	F	F	P	P	P	F	F,

Steam	E	E	F	E	E	E	F	E	E
Stearic acid	E	E	F	E	E	E	E	E	E
Sugar solutions	E	E	G	E	E	E	E	E	E
Sulfur, solid	G	G	E	G	G	G	G	E	G
Sulfur, molten	P	P	P	P	P	P	P	P	P
Sulfur chloride, dry	E	E	E	E	E	E	E	E	E
Sulfur chloride, moist	P	P	P	P	P	P	P	P	P
Sulfur dioxide, dry	E	E	E	E	E	E	E	E	E
Sulfur dioxide, moist	G	G	P	G	G	G	G	F	F
Sulfur trioxide, dry	E	E	E	E	E	E	E	E	E
Sulfuric acid 80-95%(i)	G	G	P	F	G	G	G	G	G
Sulfuric acid 40-80%(i)	F	F	F	P	F	F	F	F	F
Sulfuric acid 40%(i)	G	G	P	F	G	G	G	G	G
Sulfurous acid	G	G	P	G	G	G	G	F	F
Tannic acid	E	E	E	E	E	E	E	E	E
Tartaric acid(a)	E	E	G	E	E	E	E	E	E
Toluene	E	E	E	E	E	E	E	E	E
Trichloracetic acid	G	G	P	F	G	G	G	G	G
Trichlorethylene, dry	E	E	E	E	E	E	E	E	E

Trichlorethylene, moist	G	G	F	G	E	E	E	E	E
Turpentine	E	E	E	E	E	E	E	E	E
Varnish	E	E	E	E	E	E	E	E	E
Vinegar(a)	E	E	P	F	E	E	E	E	G
Water, acidic mine	F	F	P	F	G	F	F	P	F
Water, potable	E	E	G	E	E	E	E	E	E
Water, condensate(c)	E	E	E	E	E	E	E	E	E
Wetting agents(j)	E	E	E	E	E	E	E	E	E
Whiskey(a)	E	E	E	E	E	E	E	E	E
White water	G	G	G	E	E	E	E	E	E
Zinc chloride	G	G	P	G	G	G	G	G	G
Zinc sulfate	E	E	P	E	E	E	E	E	E

(a) Copper and copper alloys are resistant to corrosion by most food products. Traces of copper may be dissolved and affect taste or color of the products. In such cases, copper alloys are often tin coated.

(b) Acetylene forms an explosive compound with copper when moisture or certain impurities are present and the gas is under pressure. Alloys containing less than 65% Cu are satisfactory; when the gas is not under pressure, other copper alloys are satisfactory.

(c) Precautions should be taken to avoid stress-corrosion cracking (SCC).

(d) At elevated temperatures, hydrogen will react with tough pitch copper, causing failure by embrittlement.

(e) Where air is present, corrosion rate may be increased.

(f) Below 150 °C (300 °F), corrosion rate is very low; above this temperature, corrosion is appreciable and increases rapidly with temperature.

(g) Aeration and elevated temperature may increase corrosion rate substantially.

(h) Excessive oxidation may begin above 120 °C (250 °F). If moisture is present, oxidation may begin at lower temperatures.

(i) Use of high-zinc brasses should be avoided in acids because of the likelihood of rapid corrosion by dezincification. Copper, low-zinc brasses, phosphor bronzes, silicon bronzes, aluminum bronzes, and copper nickels offer good resistance to corrosion by hot and cold dilute H_2SO_4 and to corrosion by cold concentrated H_2SO_4. Intermediate concentrations of H_2SO_4 are sometimes more corrosive to copper alloys than either concentrated or dilute acid. Concentrated H_2SO_4 may be corrosive at elevated temperatures due to breakdown of acid and formation of metallic sulfides and sulfur dioxide, which cause localized pitting. Tests indicate that copper alloys may undergo pitting in 90 to 95% H_2SO_4 at about 50 °C (122 °F), in 80% acid at about 70 °C (160 °F), and in 60% acid at about 100 °C (212 °F).

(j) Wetting agents may increase corrosion rates of copper and copper alloys slightly to substantially when carbon dioxide or oxygen is present by preventing formation of a film on the metal surface and by combining (in some instances) with the dissolved copper to produce a green, insoluble compound.

Whenever there is a lack of operating experience, whenever reported test conditions do not closely match the conditions for which alloy selection is being made, and whenever there is doubt as to the applicability of published data, it is always best to conduct an independent test. Field tests are the most reliable. Laboratory tests can be equally valuable, but only if operating conditions are precisely defined and then accurately simulated in the laboratory. Long-term tests are generally preferred because the reaction that dominates the initial stages of corrosion may differ significantly from the reaction that dominates later on. If short-term tests must be used as the basis for alloy selection, the test program should be supplemented with field tests so that the laboratory results can be reevaluated in light of true operating experience.

Erroneous conclusions based on laboratory results can also be reached by measuring corrosion damage inaccurately, especially when corrosion is slight. It is common practice to express test results in terms of penetration or average reduction in metal thickness, even when corrosion was actually measured by weight loss. Weight loss or average-penetration data are valid only when corrosion is uniform. When corrosion occurs predominantly by pitting or some other localized form or when corrosion is intergranular or involves the formation of a thick, adherent scale, direct measurement of the extent of corrosion provides the most reliable information. A common technique is to measure the maximum depth of penetration observed on a metallographic cross section through the region of interest. Statistical averaging of repeated measurements on one or more specimens may or may not be warranted. Despite the deficiencies in laboratory testing, information gained in this manner serves as a useful starting point for alloy selection.

Atmospheric Exposure

Comprehensive tests conducted over a 20-year period under the supervision of the American Society for Testing and Materials (ASTM), as well as many service records, have confirmed the suitability of copper and copper alloys for atmospheric exposure (Table 5). Copper and copper alloys resist corrosion by industrial, marine, and rural atmospheres except atmospheres containing NH_3 or certain other agents where SCC has been observed in high-zinc alloys (>20% Zn). The copper metals most widely used in atmospheric exposure are C11000, C22000, C23000, C38500, and C75200. Alloy C11000 is an effective material for roofing, flashings, gutters, and downspouts.

Table 5 Atmospheric corrosion of selected copper alloys

Alloy	Corrosion rates at indicated locations(a)											
	Altoona, PA		**New York, NY**		**Key West, FL**		**La Jolla, CA**		**State College, PA**		**Phoenix, AZ**	
	μm/yr	**mils/yr**	**μm/yr**	**mils/yr**	**μm/yr**	**mils/yr**	**μm/yr**	**mils/hr**	**μm/yr**	**mils/yr**	**μm/yr**	**mils/yr**
C11000	1.40	0.055	1.38	0.054	0.56	0.022	1.27	0.050	0.43	0.017	0.13	0.005
C12000	1.32	0.052	1.22	0.048	0.51	0.020	1.42	0.056	0.36	0.014	0.08	0.005
C23000	1.88	0.074	1.88	0.074	0.56	0.022	0.33	0.013	0.46	0.018	0.10	0.004
C26000	3.05	0.120	2.41	0.095	0.20	0.008	0.15	0.006	0.46	0.018	0.10	0.004
C52100	2.24	0.088	2.54	0.100	0.71	0.028	2.31	0.091	0.33	0.013	0.13	0.005
C61000	1.63	0.064	1.60	0.063	0.10	0.004	0.15	0.006	0.25	0.010	0.51	0.002
C65500	1.65	0.065	1.73	0.068	. . .	. . .	1.38	0.054	0.51	0.020	0.15	0.006
C44200	2.13	0.084	2.51	0.099	. . .	. . .	0.33	0.013	0.53	0.021	0.10	0.004
70Cu-29Ni-1Sn(b)	2.64	0.104	2.13	0.084	0.28	0.011	0.36	0.014	0.48	0.019	0.10	0.004

(a) Derived from 20-year exposure tests. Types of atmospheres: Altoona, industrial; New York City, industrial marine; Key West, tropical rural marine; La Jolla, humid marine; State College, northern rural; Phoenix, dry rural.

(b) Although obsolete, this alloy indicates the corrosion resistance expected of C71500.

The colors of different copper alloys are often important in architectural applications, and color may be the primary criterion for selecting a specific alloy. After surface preparation, such as sanding or polishing, different copper alloys vary in color from silver to yellow to gold to reddish shades. Different alloys having the same initial color may show differences in color after weathering under similar conditions. Therefore, alloys having the same or nearly the same composition are usually used together for consistency of appearance in a specific structure.

Copper alloys are often specified for marine atmosphere exposures because of the attractive and protective patina they form during the exposure. In marine atmospheric exposures, this patina consists of a film of basic copper chloride or carbonate, sometimes with an inner layer of Cu_2O. The severity of the corrosion attack in marine atmospheres is somewhat less than that in industrial atmospheres but greater than that in rural atmospheres. However, these rates decrease with time.

Soils and Groundwater

Soils. Copper, zinc, lead, and iron are the metals most commonly used in underground construction. Data compiled by the former National Bureau of Standards (NBS) compare the behavior of these materials in soils of the following four types: well-aerated acid soils low in soluble salts (Cecil clay loam), poorly aerated soils (Lake Charles clay), alkaline soils high in soluble salts (Docas clay), and soils high in sulfides (Rifle peat).

Corrosion data as a function of time for copper, iron, lead, and zinc exposed to these four types of soil are given in Fig. 5. Copper exhibits high resistance to corrosion by these soils, which are representative of most soils found in the United States. Where local soil conditions are unusually corrosive, it may be necessary to use some means of protection, such as cathodic protection, neutralizing backfill (limestone, for example), protective coating, or wrapping.

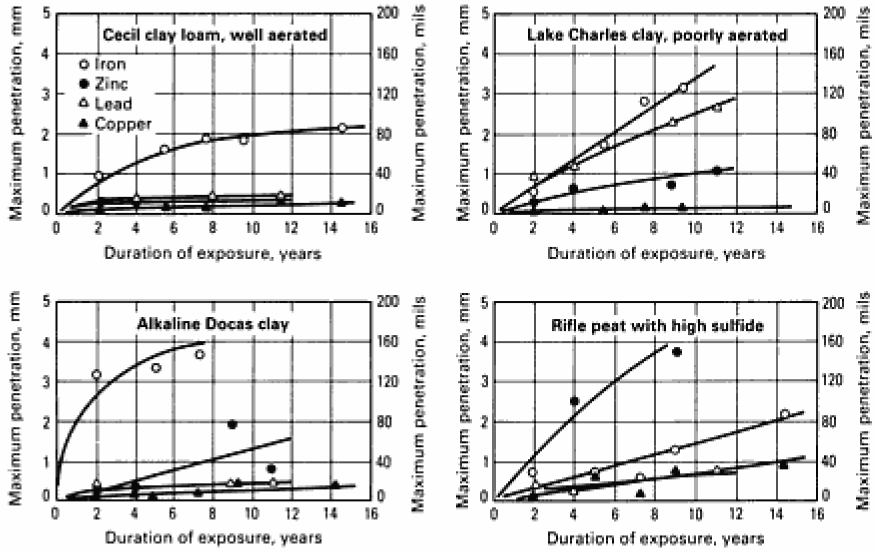

Fig. 5 Corrosion of copper, iron, lead, and zinc in four different soils

For many years, NBS (now the National Institute of Standards and Technology, or NIST) has conducted studies on the corrosion of underground structures to determine the specific behavior of metals and alloys when exposed for long periods in a wide range of soils. Results indicate that tough pitch coppers, deoxidized coppers, silicon bronzes, and low-zinc brasses behave essentially alike. Soils containing cinders with high concentrations of sulfides, chlorides, or hydrogen ions (H^+) corrode these materials. In this type of contaminated soil, the corrosion rates of copper-zinc alloys containing more than about 22% Zn increase with zinc content. Corrosion generally results from dezincification. In soils that contain only sulfides, corrosion rates of the copper-zinc alloys decrease with increasing zinc content, and no dezincification occurs. Although not included in these tests, inhibited admiralty metals would offer significant resistance to dezincification.

Groundwater. Naturally occurring saline waters are also found deep underground. Although the composition and concentration of these groundwaters vary from site to site, the concentration of dissolved species generally increases with depth. Such groundwaters are encountered in mines, during oil drilling, and in deep boreholes. The waters have a complex composition, often being mixtures of sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulfate (SO_4^{2+}) and bicarbonate (HCO_3^-) ions as well as trace amounts of other ions. Iron minerals in the bedrock react with dissolved oxygen in the groundwater and produce less oxidizing conditions than are found in waters nearer the surface.

For both copper and copper alloys, corrosion rate depends strongly on the amount of dissolved oxygen present. The data in Table 6 illustrate this point for both pure copper and Cu-10Ni in various synthetic groundwaters. These data are derived from experiments lasting from 2 to 4 weeks; therefore, they include the high initial rates of corrosion and do not represent long-term corrosion rates. However, they do serve to show that deoxygenation of the solution results in at least an order of magnitude decrease in the short-term corrosion rate. It is also apparent from these data that, in aerated solutions at least, the addition of nickel decreases the uniform corrosion rate of copper. This is due to the formation of a more highly protective surface film.

Table 6 Short-term corrosion rates of copper alloys in saline groundwaters

Alloy	Type of groundwater	Oxygen concentration, μg/g	Temperature		Corrosion rate	
			°C	**°F**	**μm/yr**	**mils/yr**
C10100	Synthetic 55 g/L TDS[a]	<0.1	150	300	15	0.6
		6	150	300	340	13.4
Copper	Brine A 306 g/L TDS[a]	<0.1	250	480	70	2.8
		600	250	480	1200	47.2
	Seawater 35 g/L TDS[a]	<0.1	250	480	50	2
		1750	250	480	5000	197
Cu-10Ni (C70600)	Brine A	<0.1	250	480	140	5.5
		600	250	480	400	15.7
	Seawater	<0.1	250	480	70	2.8
		1750	250	480	700	27.6

(a) TDS, total dissolved solids

Water

Freshwater. Copper is extensively used for handling freshwater. Copper tubing in the K-gage range with flared fittings was designed for underground water service and, along with type L tubing, has now become standard for this application. The largest single application of copper tubing is for hot- and cold-water distribution lines in homes and other buildings, although considerable quantities are also used in heating lines (including radiant heating lines for homes), drain tubes, and fire safety systems.

Steam. Copper and copper alloys resist attack by pure steam, but if much CO_2, oxygen, or NH_3 is present, the condensate is corrosive. Even though wet steam at high velocities can cause severe impingement attack, copper alloys are extensively used in condensers and heat exchangers. Copper alloys are also used for feedwater heaters, although their use in such applications is somewhat limited because of their rapid decline in strength and creep resistance at moderately elevated temperatures. Copper nickels are the preferred copper alloys for the higher temperatures and pressures.

Use of copper in systems handling hot water and steam is limited by the working pressures of tubes and joints. For example, copper tubing of 6.4 to 25 mm ($\frac{1}{4}$ to 1 in.) nominal diameter joined with 50Sn-50Pb solder can be used at temperatures to 120 °C (250 °F) and pressures to 585 kPa (85 psi). The working pressure at this temperature in tubing of the same size can be increased to 1380 kPa (200 psi) when the system is joined with 95Sn-5Sb solder. When the joining material is a silver-base brazing alloy with a melting point above 540 °C (1000 °F), the working pressure at 120 °C (250 °F) for tubing in this size range can be increased to 2070 kPa (300 psi). A few copper alloys have shown a tendency to fail by SCC when they are highly stressed and exposed to steam. Alpha aluminum bronzes that do not contain tin are among the susceptible alloys.

Steam condensate that has been properly treated so that it is relatively free of noncondensate gases, as in a power-generating station, is relatively noncorrosive to copper and copper alloys. Rates of attack in such exposures are less than 25 μm/year (0.1 mil/year). Copper and copper alloys are not attacked by condensate that contains a significant amount of oil, such as condensate from a reciprocating steam engine.

Dissolved CO_2, oxygen, or both significantly increase the rate of attack. For example, condensate with a 4.6 ppm O, and 14 ppm CO_2, and a pH of 5.5 at 68 °C (155 °F) caused an average penetration of 175 to 350 μm/year (6.9 to 13.8 mils/year) when in contact with C12200 (phosphorus-deoxidized copper), C14200 (arsenical copper), C23000 (red brass), C44300 to C44500 (admiralty metal), and C71000 (copper nickel, 20%). Steel tested under the same conditions was penetrated at about twice the rate given for the copper alloys listed above, but tin-coated copper proved to be much more resistant and was attacked at a rate of less than 25 μm/year (1 mil/year). To attain the optimum service life in condensate systems, it is necessary to ensure that the tubes are installed with enough slope to allow proper drainage, to reduce the quantity of corrosive agents (usually CO_2 and oxygen) at the source by mechanical or chemical treatment of feedwater, or to treat the steam chemically.

Salt Water. An important use of copper alloys is in handling seawater in ships and tidewater power stations. Copper itself, although fairly useful, is usually less resistant to general corrosion than C44300 to C44500, C61300, C68700, C70600, or C71500. The superior performance to these alloys results from the combination of insolubility in seawater, erosion resistance, and biofouling resistance. The corrosion rates of copper and copper alloys in relatively quiescent seawater are typically less than 50 μm/year (2 mils/year).

In the laboratory and in service, copper-nickel alloys C70600, C71500, C72200, and C71640 exhibit excellent corrosion resistance in seawater. Average corrosion rates for both C70600 and C71500 range from 2 to 12 μm/year (0.08 to 0.5 mil/year). Long-term evaluations have revealed corrosion rates under 2.5 μm/year (0.1 mil/year) for both alloys after 14 years of exposure to quiescent and low-velocity seawater.

Polluted cooling waters, particularly in coastal harbors and estuaries, have caused premature failures of power station and shipboard condensers using copper-base alloys, including the copper-nickels. Although enforcement of strict pollution standards has dramatically reduced pollution in many harbors in recent years, accelerate attack of condenser tubes and seawater piping materials by polluted waters is still reported.

The primary causes of accelerated attack of copper-base alloys in polluted seawater are (1) the action of sulfate-reducing bacteria, under anaerobic conditions (for example, in bottom muds or sediments), on the natural sulfates present in seawater and (2) the putrefaction of organic sulfur compounds from decaying plant and animal matter within seawater systems during periods of extended shutdown. Corrosion resistance can be enhanced by proper design, the use of inhibitors, or by adding iron to the seawater (by additions of ferrous sulfate or sacrificial iron anodes).

Biofouling. Copper alloys, including the copper-nickels, have long been recognized for their inherent resistance to marine fouling. This fouling resistance is usually associated with macrobiological fouling, such as barnacles, mussels, and marine invertebrates of corresponding size. Service experience with shrimp trawlers and private yachts fabricated with C70600 or D71500 hulls has demonstrated excellent resistance to hard-shell fouling and an accompanying reduction in hull maintenance costs. Copper-nickel alloys have also performed successfully as seawater intake screens by virtue of their mechanical strength, corrosion resistance, and resistance to biofouling.

Heat Exchangers and Condensers. The selection of material for condenser and heat-exchanger tubes necessitates a survey of service conditions, an examination of tubes previously used and evaluation of its service life, and a review of the type, form, and location of corrosion experience in the unit or in similar units. Types of water and operating conditions vary widely, and any estimate of probable tube performance must be based on specific operating factors. Tubes of various alloys, inhibited admiralty metal (C44300, C44400, and C44500), inhibited aluminum brass (C68700), aluminum bronzes (C61300 and C63200), copper nickels (C70600 and C71500) and phosphorus-deoxidized coppers (C12000 to C12300), have all been found to give satisfactory and economical performance in these applications.

Acids

Copper is widely employed for industrial equipment used to handle acid solutions. A fairly definite separation exists between those acids that can be handled by copper and those that cannot. In general, copper alloys are successfully used with nonoxidizing acids, such as acetic (CH_3COOH), sulfuric (H_2SO_4), hydrochloric (HCl), and phosphoric (H_3PO_4), as along as the concentration of oxidizing agents, such as dissolved oxygen (air) and ferric (Fe^{3+}) or dichromate ions, is low. Broadly speaking, a thoroughly agitated or stirred solution or one into which a stream of air has been bubbled approaches air saturation and is therefore not a suitable acid medium for copper. Acids that are oxidizing agents in themselves, such as HNO_3; sulfurous (H_2SO_3); hot, concentrated H_2SO_4; and acids carrying such oxidizing agents as Fe^{3+} salts, dichromate ions, or permanganate (MnO_4^-) ions cannot be handled in equipment made of copper or its alloys.

The corrosive action of a dilute (up to 1% acid) nonoxidizing acid on copper is relatively low; corrosion rates are usually less than 6 g/m^2/d (equivalent penetration rate: 250 μm/year, or 10 mils/year). This is true only of oxidizing acids when the concentration does not exceed 0.01%. At such low acid concentrations, aeration has little effect in either oxidizing or nonoxidizing acids.

Nonoxidizing acids with near-zero aeration have virtually no corrosive effect. Rates in 1.2 *N* H_2SO_4, HCl, and CH_3COOH are less than 0.1 g/m^2/day (4 μm/year, or 0.15 mil/year) in the absence of air.

Except for HCl, nonoxidizing acids that contain as much air as is absorbed in quiet contact with the atmosphere are weakly corrosive. Rates generally range from 0.5 to 6 g/m^2 per day (approximately 20 to 250 μm/year, or 0.8 to 10 mils/year).

Air-saturated solutions of nonoxidizing acids are likely to be strongly corrosive, with corrosion rates of 5 to 30 g/m^2/d (0.2 to 1.25 mm/year, or 8 to 50 mils/year). This rate is higher for HCl. The actual corrosion in any aerated acid depends on acid concentration, temperature, and other factors that are difficult to classify. Except in very dilute solutions, oxidizing acids corrode copper rapidly--usually at rates above 50 g/m^2/day (2.1 mm/year, or 85 mils/year). The reaction is independent of aeration.

The corrosion rate of three common acids are compared in the following table (temperature and aeration are not specified):

Acid	Corrosion rate		
	g/m^2/d	**mm/yr**	**mils/yr**
32% HNO_3	5700	240	9450
Concentrated HCl	18	0.75	30
17% H_2SO_4	2	0.1	4

Phosphoric, CH_3COOH, tartaric, formic, oxalic, malic, and similar acids normally react comparably to H_2SO_4.

Alkalies

Copper and copper alloys resist alkaline solutions, except those containing ammonium hydroxide (NH_4OH) or compounds that hydrolyze to NH_4OH or cyanides. Ammonium hydroxide reacts with copper to form soluble complex copper cations, but the cyanides react to form soluble complex copper anions. The rate of attack for copper-zinc alloys exposed to alkalies other than those specified previously (e.g., sodium hydroxide) is ~50 to 500 μm/year (2 to 20 mils/year) at room temperature under stagnant conditions, but is about 500 to 1750 μm/year (20 to 70 mils/year) in aerated boiling solutions.

Strong NH_4OH solutions attack copper and copper alloys rapidly, as compared with the rates of attack by metallic hydroxides because of the formation of a soluble complex copper-ammonium compound. However, in some applications, the corrosion of copper exposed to dilute solutions of NH_4OH is low. For example, copper specimens submerged in 0.1 *N* NH_4OH solution at room temperature for 1 week experienced weight loss of 1.5 m/m^{2}day (60 μm/year, or 2.5 mils/year).

Ammonium hydroxide solutions also attack copper-zinc alloys. Alloys containing more than 15% Zn are susceptible to SCC when exposed to NH_4OH. The stress may be due to applied service loads or to unrelieved residual stresses. In quiescent 2 *N* NH_4OH solutions at room temperature, copper-zinc alloys corrode at 1.8 to 6.6 mm/year (70 to 260 mils/year), copper-nickel alloys at 0.25 to 0.50 mm/year (10 to 20 mils/year), copper-tin alloys at 1.3 to 2.5 mm/year (50 to 100 mils/year), and copper silicon alloys at 0.75 to 5 mm/year (30 to 200 mils/year).

Copper and copper alloys are suitable for handling anhydrous NH_3 if the NH_3 remains anhydrous and is not contaminated with water and oxygen. In one test conducted for 1200 h, C11200 and C26000 each showed an average penetration of 5 μm/year (0.2 mil/year) in contact with anhydrous NH_3 at atmospheric temperature and pressure.

Salts

Copper metals are widely used in equipment for handling saline solutions of various kinds, particularly those that are nearly neutral. Among these are the nitrates, sulfates, and chlorides of sodium and potassium. Chlorides are usually more corrosive than the other salts, especially in strongly agitated, aerated solutions.

The nonoxidizing acid salts, such as the alums and certain metal chlorides (magnesium and calcium chlorides) that hydrolyze in water to produce an acidic pH, exhibit essentially the same behavior as dilute solutions of the corresponding acids. Corrosion rates generally range from 2.5 to 1500 μm/year (0.1 to 60 mils/year) at room temperature, depending on the degree of aeration and the acidity.

Neutral saline solutions can be successfully handled by copper alloys. Consequently, these alloys are used in heat exchanger and condenser equipment exposed to seawater.

Such alkaline salts as sodium silicate (Na_2SiO_3), sodium phosphate (Na_2CO_3) attack copper alloys at low but different rates at room temperature. On the other hand, alkali cyanide is aggressive and attacks copper alloys fairly rapidly because it forms a soluble complex copper anion.

Oxidizing salts corrode copper and copper alloys rapidly; therefore, copper metals should not be used with oxidizing saline solutions except those that are very dilute. Aqueous sodium dichromate ($Na_2Cr_2O_7$) solutions can be safely handled by copper alloys, but the presence of a highly ionized acid, such as H_2CrO_4 or H_2SO_4, may increase the corrosion rate several hundred times, because the dichromate acts as an oxidizing agent in acidic solutions. In one test, a copper-nickel corroded at 2.5 to 250 μm/year (0.1 to 10 mils/year) and a copper-tin alloy (phosphor bronze) at 5 μm/year (0.2 mil/year) when handling an aqueous $Na_2Cr_2O_7$ solution. The rate increased 200 to 300 times for both metals when H_2CrO_4 was added to the solution. In solutions containing Fe^{3+}, mercuric (Hg^{2+}) or stannic (Sn^{4+}) ions, a copper-nickel showed a corrosion rate of 27.4 mm/year (1080 mils/year), while copper-zinc and copper-tin alloys showed a still greater rate of 228 mm/year (8980 mils/year).

Salts of metals more noble than copper, such as the nitrates of mercury and silver, corrode copper alloys rapidly, simultaneously plating out the noble metal on the copper surface. Temperature and acidity influence the rate of attack. A film of mercury on high-zinc brass (more than 15% Zn) can cause intergranular cracking by liquid-metal embrittlement (LME) if the alloy is under tensile stress, either residual or applied.

Organic Compounds

Copper and many copper alloys resist corrosive attack by most organic solvents and by organic compounds, such as amines, alkanolamines, esters, glycols, ethers, ketones, alcohols, aldehydes, naphtha, and gasoline. Although the corrosion rates of copper and copper alloys in pure alkanolamines and amines are low, they can be significantly increased if these compounds are contaminated with water, acids, alkalies, salts, or combinations of these impurities, particularly at high temperatures.

Gasoline, naphtha, and other related hydrocarbons in pure form will not attack copper or any of the copper alloys. However, in the manufacture of hydrocarbon materials, process streams are likely to be contaminated with one or more of such substances as water, sulfides, acids, and various organic compounds. These contaminants attack copper and copper alloys. Corrosion rates for C44300 and C71500 exposed to gasoline are low and these two alloys are successfully used in equipment for refining gasoline.

Creosote. Copper and copper alloys are generally suitable for use with creosote, although creosote attacks some high-zinc brasses. Alloys C11000, C23000, C26000, C51000, and C65500 typically corrode at rates less than 500 μm/year (2 mils/year) when exposed to creosote at 25 °C (75 °F).

Linseed Oil. Copper and copper alloys are fairly resistant to corrosion by linseed oil. All of the alloys show some attack, but none exhibits corrosion severe enough to make it unsuitable for this application. Alloys C11000, C51000, and C65500 showed corrosion rates less than 500 μm/year (20 mils/year) in linseed oil at 25 °C (75 °F). Alloy C26000 had a rate of 500 to 1250 μm/year (20 to 50 mils/year).

Benzol and Benzene. Alloys C11000, 23000, C26000, C51000, and C65500 tested in these materials at 25 °C (75 °F) had corrosion rates under 500 μm/year (20 mils/year).

Sugar. Copper is successfully used for vacuum-pan heating coils, evaporators, and juice extractors in the manufacture of both cane and beet sugar. Inhibited admiralty metals, aluminum bronzes, and copper nickels are also used for tubes in juice heaters and evaporators. Bimetal tubes of copper and steel have been used by manufacturers of beet sugar to counteract SCC of copper tubes caused by NH_3 from beets grown in fertilized soil.

Beer. Copper is extensively used in the brewing of beer. In one installation, the wall thickness of copper kettles thinned from an original thickness of 16 mm ($\frac{5}{8}$ in.) to 10 mm ($\frac{3}{8}$ in.) in a 30-year period. Brazing with BAg (copper-silver) filler metals eliminates the possibility that the alkaline compounds used for cleaning copper equipment will destroy joints by attacking tin-lead solders. Steam coils require more frequent replacement than any other component in brewery equipment. They have service lives of 15 to 20 years. The service lives of other copper items exposed to process streams in a brewery range from 30 to 40 years.

Sulfur compounds free to react with copper, hydrogen sulfide (H_2S), sodium sulfide (Na_2S), or potassium sulfide (K_2S), form CuS. Reaction rates depend on alloy composition; the alloys of highest resistance are those of high zinc content (e.g., 60Cu-40Zn).

Inhibited admiralty metals are also excellent alloys for use in heat exchangers and condensers that handle sulfur-bearing petroleum products and use water as the coolant. Alloys C44300, C44400, and C44500, which are inhibited toward dezincification by the addition of arsenic, antimony, or phosphorus to the basic 70Cu-29Zn-1Sn composition, offer good resistance to corrosion from sulfur as well as excellent resistance to the water side of the heat exchanger.

Protective Coatings

Copper metals resist corrosion in many environments because they react with one or more constituents of the environment upon initial exposure, thus forming an inert surface layer of protective reaction products. In certain applications, the corrosion resistance of copper metals can be increased by applying metallic or organic protective coatings. If the coating material is able to resist corrosion adequately, service life may depend on the impermeability, continuity, and adhesion to the basis metal of the coating. The electropotential relationship of the coating to the basis metal may be important, especially with metallic coatings and at uncoated edges. Tin, lead, and solder, used extensively as coatings, are ordinarily applied by hot dipping. Electroplating is also used.

Tin affects corrosion caused by sulfur; it is most effective as a coating for copper wire and cable insulated by rubber that contains sulfur. Lead-coated copper is primarily used for roofing applications, in which contact with flue gases or other products that contain dilute H_2SO_4 is likely. Tin or lead coatings are sometimes applied to copper intended for ordinary atmospheric exposure, but this is done primarily for architectural effect; the atmospheric-corrosion resistance of bare copper is excellent in rural, urban, marine, and most industrial locations.

Electroplated chromium is used for decoration, for improvement of wear resistance, or for reflectivity. Because it is somewhat porous, it is not effective for corrosion protection. Where corrosion protection is important, electroplated nickel is most often used as a protective coating under electroplated chromium.

Various organic coatings are applied to copper alloys to preserve a bright metallic appearance.

Manufacture of Cemented Carbides

All cemented carbide components are manufactured by powder metallurgy (P/M) processing. As described below, the important steps include powder processing, production of grade (alloy) powders, powder consolidation, sintering, and finishing.

Powder Processing. Tungsten carbide is manufactured through the reduction of tungsten oxide and subsequent carburization at 1400 to 1500 °C (2550 to 2730 °F). Particle sizes range from 0.5 to 3.0 μm.

Cobalt is manufactured through reduction of cobalt oxides or derived from organic salts--particularly cobalt oxalate. The cobalt binder phase is altered significantly during milling with WC and subsequent liquid-phase sintering operations.

The TiC/TaC/NbC powders are produced from metal oxides of titanium, tantalum, and niobium. These oxides are mixed with metallic tungsten powder and carbon similar to the preparation of WC powder. The mixture is heated under a hydrogen atmosphere or vacuum to reduce the oxides and form solid-solution carbides. The Menstruum process is also effective for the production of mixed carbide.

Production of Grade Powders. Cemented carbide grade powders are produced by combining WC with cobalt or nickel binder and, depending on the application, varying amounts of TaC/TiC/NbC. The grade powder is milled in conventional ball mills, attrition mills, or vibratory mills. The milling process reduces the particle size of the raw materials and also provides uniformity of mixture. Milling operations are typically carried out in a protective solvent to minimize heating and subsequent oxidation of the powder, and to disperse the powder particles to achieve intimate mixing. During the grade powder manufacturing process, 2 to 3 wt% of a solid lubricant such as paraffin wax is added. This lubricant reduces the potential for oxidation and provides green strength to as-pressed components. The lubricant/solvent/powder slurry is then dried to remove the solvent. Spray drying is the most widely used method of powder drying. The slurry is atomized through a nozzle and sprayed into a stream of nitrogen gas. The solvent is vaporized, condensed outside the chamber, and reused. The dried powder is now in the form of free-flowing spherical aggregates on the order of 150 to 250 μm in diameter.

Powder consolidation processes include a number of vastly different techniques. Many wear components are produced on automatic or semiautomatic presses at pressures of 50 to 150 MPa (7 to 22 ksi). In cold isostatic pressing, the grade powder is consolidated into a rough billet or ingot using equal pressure from all directions. This rough billet is then preformed or machined to a net shape. Extrusion of carbide grade powders is used to produce long components of small, constant cross section. There has also been limited injection molding of cemented carbides.

Sintering operations are carried out in batch-type or semicontinuous furnaces in either a vacuum, hydrogen, or other inert atmosphere. A 400 to 500 °C (750 to 930 °F) hold dewaxes the parts, and the vaporized lubricant is condensed outside the heating chamber and discarded. Final sintering takes places at 1300 to 1600 °C (2370 to 2910 °F); the precise temperature depends on the cobalt content--the grades with the higher cobalt contents have the lower sintering temperatures. The final sintering temperature is above the eutectic temperature of the carbide-binder system, and the binder partially melts. The excellent wettability of WC by cobalt results in rapid liquid-phase sintering, which promotes coalescence of the WC particles and produces a fully dense, virtually porosity-free microstructure. Linear shrinkage on the order of 15 to 25% takes place.

The advantages of hot isostatic pressing (HIP) have been exploited since the early 1970s. Components requiring high reliability and/or surface integrity are HIPed to eliminate residual porosity, pits, or flaws. Materials are heated to a temperature above the liquidus, and the vessel is pressurized with an inert gas to slightly less than 100 MPa (15 ksi). The combination of pressure and temperature forces the binder into any residual pits or porosity. Recent advances have combined liquid-phase sintering and HIP into a single sinter-HIP process. Sinter-HIP uses lower pressures and higher temperatures than conventional HIP with no sacrifice in component reliability. The resulting sinter-HIP microstructure is more uniform than that produced by conventional HIP, and sinter-HIP is more cost effective.

Finishing operations include grinding with diamond wheels, electrical discharge machining (EDM) using wire or shaped electrodes, and edge honing using a variety of abrasive techniques. Final lapping to mirrorlike finishes is accomplished using diamond-containing slurries or pastes.

Cemented Carbides for Machining Applications

The performance of cemented carbides as a cutting tool lies between that of tool steel and cermets. Compared to tool steels, cemented carbides are harder and more wear resistant, but also exhibit lower fracture resistance and thermal conductivities than tool steels. Cermets, on the other hand, are more wear resistant than cemented carbides, but may not be as tough. The performance of either carbide or cermet cutting tools is strongly dependent on composition and microstructure, and the properties of cemented carbide tools depend not only on the type and amount of carbide but also on the carbide grain size and the amount of binder metal (see the discussion below on "Structure/Property Relationships").

Tungsten Carbide-Cobalt Alloys. The first commercially available cemented carbides consisted of WC particles bonded with cobalt. These are commonly referred to as straight grades. These alloys exhibit excellent resistance to simple abrasive wear and thus have many applications in metal cutting. Table 1 lists the representative properties of several straight WC-Co alloys.

Table 1 Properties of representative cobalt-bonded cemented carbides

Nominal composition	Grain size	Hardness, HRA	Density		Transverse strength		Compressive strength		Modulus of elasticity		Relative abrasion resistance[a]	Coefficient of thermal expansion, μm · K		Thermal conductivity, W/m · K
			g/cm^3	**$oz/in.^3$**	**MPa**	**ksi**	**MPa**	**ksi**	**GPa**	**10^6 psi**		**at 200 °C (390 °F)**	**at 1000 °C (1830 °F)**	
97WC-3Co	Medium	92.5-93.2	15.3	8.85	1590	230	5860	850	641	93	100	4.0	. . .	121
97WC-6Co	Fine	92.5-93.1	15.0	8.67	1790	260	5930	860	614	89	100	4.3	5.9	. . .
	Medium	91.7-92.2	15.0	8.67	2000	290	5450	790	648	94	58	4.3	5.4	100
	Coarse	90.5-91.5	15.0	8.67	2210	320	5170	750	641	93	25	4.3	5.6	121
90WC-10Co	Fine	90.7-91.3	14.6	8.44	3100	450	5170	750	620	90	22	. . .	. . .	. . .
	Coarse	87.4-88.2	14.5	8.38	2760	400	4000	580	552	80	7	5.2	. . .	112
84WC-16Co	Fine	89	13.9	8.04	3380	490	4070	590	524	76	5	. . .	. . .	. . .
	Coarse	86.0-87.5	13.9	8.04	2900	420	3860	560	524	76	5	5.8	7.0	88
75WC-25Co	Medium	83-85	13.0	7.52	2550	370	3100	450	483	70	3	6.3	. . .	71
71WC-12.5TiC-12TaC-4.5Co	Medium	92.1-92.8	12.0	6.94	1380	200	5790	840	565	82	11	5.2	6.5	35

72WC-8TiC-11.5TaC-8.5Co	Medium	90.7-91.5	12.6	7.29	1720	250	5170	750	558	81	13		5.8	6.8	50

(a) Based on a value of 100 for the most abrasion-resistant material

The commercially significant alloys contain cobalt in the range of 3 to 25 wt%. For machining purposes, alloys with 3 to 12% Co and carbide grain sizes from 0.5 to more than 5 μm are commonly used.

The ideal microstructure of WC-Co alloys should exhibit only two phases: angular WC grains and cobalt binder phase. Representative microstructures of several straight WC-Co alloys are shown in Fig. 1. The carbon content must be controlled within narrow limits. Too high a carbon content results in the presence of free and finely divided graphite (C-type porosity), which in small amounts has no adverse effects in machining applications. Deficiency in carbon, however, results in the formation of a series of double carbides (for example, Co_3W_3C or Co_6W_6C), commonly known as ηphase, which causes severe embrittlement.

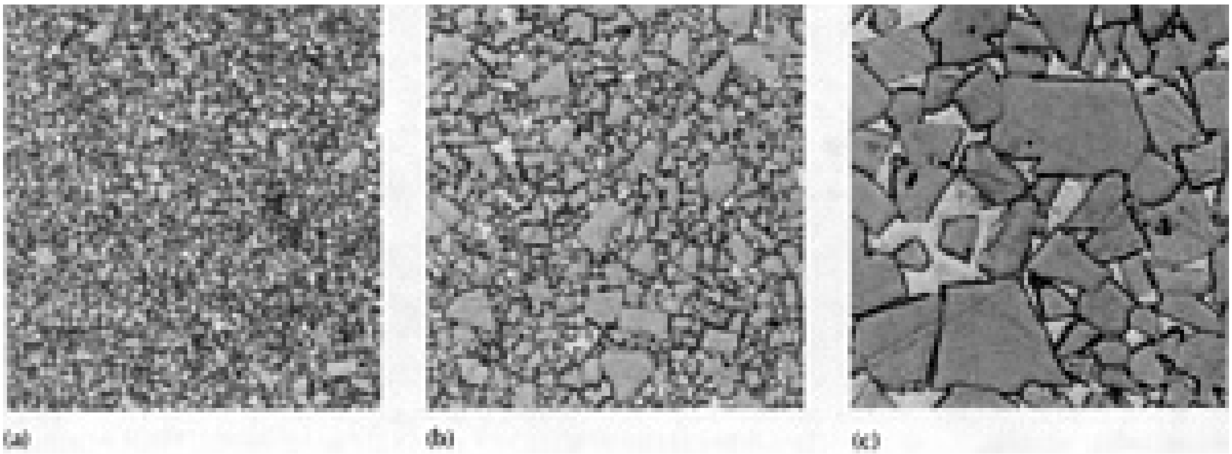

Fig. 1 Microstructures of 90WC-10Co cemented carbide (straight grade). The light constituent is the cobalt binder. (a) Fine grain size. (b) Medium grain size. (c) Coarse grain size. All at 1500×

Submicron Tungsten Carbide-Cobalt Alloys. In recent years, WC-Co alloys with submicron carbide grain sizes have been developed for applications requiring more toughness or edge strength. Typical applications include indexable inserts and a wide variety of solid carbide drilling and milling tools. Grain refinement in these alloys is obtained by small additions (0.25 to 3.0 wt%) of TaC, NbC, VC, or CrC. Additions can be made before carburization of the tungsten or later in the powder blend.

Alloys Containing Tungsten Carbide, Titanium Carbide, and Cobalt. The WC-Co alloys, developed in the early 1920s, were successful in the machining of cast iron and nonferrous alloys at much higher speeds than were possible with high-speed steel tools, but were subject to chemical attack or diffusion wear when cutting steel. As a result, the tools failed rapidly at speeds not much higher than those used with high-speed steel. This led to the development of WC-TiC-Co alloys.

Tungsten carbide diffuses readily into the steel chip surface, but the solid solution of WC and TiC resists this type of chemical attack. Unfortunately, TiC and WC-TiC solid solutions are more brittle and less abrasion resistant than WC. The amount of TiC added to WC-Co alloys is therefore kept to a minimum, typically no greater than 15 wt%. The carbon content is less critical in WC-TiC-Co alloys than in WC-Co alloys, and the ηphase does not appear in the microstructure unless carbon is grossly inadequate. In addition, free graphite rarely occurs in these alloys.

Complex Grades. The WC-TiC-Co alloys have given way to alloys of WC, cobalt, TiC, TaC, and NbC. The WC-Co alloys containing TiC, TaC, and NbC are called complex grades, multigrades, or steel-cutting grades. Adding TaC to WC-TiC-Co alloys partially overcomes the deleterious effect of TiC on the strength of WC-Co alloys. Tantalum carbide also resists cratering and improves thermal shock resistance. The latter property is particularly useful in applications involving interrupted cuts. Tantalum carbide is often added as (Ta,Nb)C because the chemical similarity between TaC and NbC makes their separation expensive. Fortunately, NbC has an effect similar to TaC in most cases. Unlike the WC-Co alloys, the microstructure of WC-TiC-(Ta,Nb)C-Co alloys shows three phases: angular WC grains, rounded WC-TiC-(Ta,Nb)C solid-solution grains, and cobalt binder (Fig. 2). The size and distribution of the phases vary widely, depending on the amounts and grain sizes of the raw materials employed and on the method of manufacture. Similarly, the properties of these complex alloys also vary widely, as indicated in Table 1 for representative steel-cutting grades.

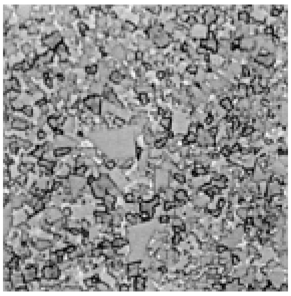

Fig. 2 Microstructure of 85WC-9(Ta,Ti,Nb)C-6Co steel-cutting grade of cemented carbide, medium grain size. The gray angular particles are WC, and the dark gray, rounded particles are solid-solution carbides. The white areas are cobalt binder. 1500×

Classification of Cemented Carbides

There is no universally accepted system for classifying cemented carbides. The systems most often employed by producers and users are discussed below.

C-Grade System. The U.S. carbide industry uses an application-oriented system of classification to assist in the selection of proper grades of cemented carbides. This C-grade system does not require the use of tradenames for identifying specific carbide grades (Table 2). Although this classification simplifies tool application, it does not reflect the material properties that significantly influence selection of the proper carbide grade. Additionally, the definitions of work materials involved in this classification scheme are imprecise. There is also no universal agreement on the meanings of the terms used to describe the various application categories. Despite these limitations, the C-grade classification has been successfully used by the manufacturing industry since 1942.

Table 2 C-grade classification of cemented carbides

C-grade	Application category
Machining of cast iron, nonferrous, and nonmetallic materials	
C-1	Roughing
C-2	General-purpose machining
C-3	Finishing
C-4	Precision finishing

Machining of carbon and alloy steels	
C-5	Roughing
C-6	General-purpose machining
C-7	Finishing
C-8	Precision finishing
Nonmachining applications	
C-9	Wear surface, no shock
C-10	Wear surface, light shock
C-11	Wear surface, heavy shock
C-12	Impact, light
C-13	Impact, medium
C-14	Impact, heavy

ISO Classification. In 1964, the International Organization of Standardization (ISO) issued ISO Recommendation R513 "Application of Carbides for Machining by Chip Removal." The basis for the ISO classification of carbides is summarized in Table 3.

Table 3 ISO R513 classification of carbides according to use for machining

Designation(a)	Groups of applications	
	Material to be machined	**Use and working conditions**
P01	Steel, steel castings	Finish turning and boring; high cutting speeds, small chip section, accuracy of dimensions and fine finish, vibration-free operation
P10	Steel, steel castings	Turning, copying, threading, and milling; high cutting speeds, small or medium chip sections
P20	Steel, steel castings, malleable cast iron with long chips	Turning, copying, milling, medium cutting speeds and chip sections; planing with small chip sections

P30	Steel, steel castings, malleable cast iron with long chips	Turning, milling, planing, medium or low cutting speeds, medium or large chip sections, and machining in unfavorable conditions(b)
P40	Steel, steel castings with sand inclusion and cavities	Turning, planing, slotting, low cutting speeds, large chip sections with the possibility of large cutting angles for machining in unfavorable conditions(b) and work on automatic machines
P50	Steel, steel castings of medium or low tensile strength, with sand inclusion and cavities	For operations demanding very tough carbide; turning, planing, slotting, low cutting speeds, large chip sections, with the possibility of large cutting angles for machining in unfavorable conditions(b) and work on automatic machines
M10	Steel, steel castings, manganese steel, gray cast iron, alloy cast iron	Turning, medium or high cutting speeds; small or medium chip sections
M20	Steel, steel castings, austenitic or manganese steel, gray cast iron	Turning, milling; medium cutting speeds and chip sections
M30	Steel, steel castings, austenitic steel, gray cast iron, high-temperature-resistant alloys	Turning, milling, planing; medium cutting speeds, medium or large chip sections
M40	Mild free-cutting steel, low-tensile steel, nonferrous metals, and light alloys	Turning, parting off, particularly on automatic machines
K01	Very hard gray cast iron, chilled castings of >85 scleroscope hardness, high-silicon aluminum alloys, hardened steel, highly abrasive plastics, hard cardboard, ceramics	Turning, finish turning, boring, milling, scraping
K10	Gray cast iron >220 HB, malleable cast iron with short chips, hardened steel, silicon aluminum alloys, copper alloys, plastics, glass, hard rubber, hard cardboard, porcelain, stone	Turning, milling, drilling, boring, broaching, scraping
K20	Gray cast iron up to 200 HB, nonferrous metals; copper, brass, aluminum	Turning, milling, planing, boring, broaching, demanding very tough carbide
K30	Low-hardness gray cast iron, low-tensile steel, compressed wood	Turning, milling, planing, slotting, for machining in unfavorable conditions(b) and with the possibility of large cutting angles
K40	Softwood or hardwood, nonferrous metals	Turning, milling, planing, slotting, for machining in unfavorable conditions(b) and with the possibility of large cutting angles

(a) In each letter category, low designation numbers are for high speeds and light feeds; higher numbers are for slower speeds and/or heavier feeds. Also, increasing designation numbers imply increasing toughness and decreasing wear resistance of the cemented carbide materials.

(b) Unfavorable conditions include shapes that are awkward to machine; material having a casting or forging skin; material having variable hardness; and machining that involves variable depth of cut, interrupted cut, or moderate to severe vibrations.

In the ISO system, all machining grades are divided into three color-coded groups:

- Highly alloyed WC grades (letter P, blue color) for machining steel
- Alloyed WC grades (letter M, yellow color, generally with less TiC than the corresponding P series) for multipurpose use, such as steels, nickel-base superalloys, and ductile cast irons
- Straight WC grades (letter K, red color) for cutting gray cast iron, nonferrous metals, and nonmetallic materials

Each grade within a group is assigned a number to represent its position from maximum hardness to maximum toughness. P-grades are rated from 01 to 50, M-grades from 10 to 40, and K-grades from 01 to 40. Typical applications are described for grades at more or less regular numerical intervals.

Properties of Cemented Carbides

Structure / Property Relationships. Specific properties of individual grades of cemented carbides depend not only on the composition of the carbide but also on its grain size and on the amount and type of binder.

The compositions and properties of nine straight grades and two complex grades of cobalt-bonded carbide are given in Table 1. Because properties are influenced by both composition and structure, both characteristics must be specified to define a specific grade.

For straight WCs of comparable WC grain size, increasing cobalt content increases transverse strength and toughness but decreases hardness, compressive strength, elastic modulus, and abrasion resistance. If, for example, medium-grain carbides having 3, 7, and 25% Co are compared, 3% Co grade is found to have the greatest hardness and abrasion resistance--properties that make it well suited for wiredrawing dies and for cutting tools used in machining of cast iron and other abrasive or gummy materials. The 6% Co grade has moderate values for all properties and is a good general-purpose carbide material. The 25% Co grade has the greatest toughness and is used for applications involving heavy impact. Because of its relatively low hardness and abrasion resistance, it is not used for cutting tools. Similar parallels in properties and uses can be drawn both for the fine-grain grades and for the coarse-grain grades containing 6, 10, and 16% Co.

Another set of comparisons can be drawn for the grades containing 6% Co. All three grades--fine, medium, and coarse--are used for cutting tools, but the applications to which they are applied involve different machining conditions and different work materials. The fine-grain material is used for finish to medium-rough machining of ductile, gray, and chilled irons and of austenitic stainless steels, high-temperature alloys, and nonmetallic materials; the medium-grain material for light to heavy machining of these same wrought work materials; and the coarse-grain grade for heavy to extremely heavy rough machining of such materials. The medium-grain material is widely employed for general-purpose machining because its properties have been found to offer a good practical balance between hardness and toughness. The coarse-grain grade, which has the lowest hardness and abrasion resistance and the best toughness of the three grades, is used where a combination of moderate hardness and high toughness is needed. Similar comparisons can be made for the grades that contain 10 and 16% Co. In general, decreasing grain size improves abrasion resistance and makes it easier to retain the edge on a cutting tool; increasing grain size improves toughness and makes the cemented carbide more suitable for die applications.

For complex grades, comparisons similar to those drawn for the straight grades are not as readily made. Variations in carbide type, as well as in binder content, affect properties, which in turn influence suitability for specific types of service.

The two complex grades listed in Table 1 contain about the same amount of WC, but one contains about twice as much binder. The lower-cobalt grade is used for lighter-duty cutting. The complex grade high in TiC is relatively low in transverse strength and high in resistance to abrasion and cratering. It is used extensively for high-speed, light-duty finishing. The complex grade highest in cobalt content and in TaC is preferred for hot-work tools, in both cutting and shaping of metals.

Hardness is typically measured on the Rockwell A scale with values ranging from 83.0 HRA for high-cobalt coarse-grain grades to 93.0 HRA for low-cobalt fine-grain grades. Vickers diamond pyramid hardness (HV) is widely used in Europe; values range from 800 to 2000 kg/mm^2 using a 30 kg load. The precision and accuracy of hardness testing is influenced significantly by the surface finish of the testpiece, parallelism between top and bottom surfaces, and the quality of hardness standards and diamond penetrators. For straight WC-Co grades with comparable WC grain size, hardness decreases with increasing binder content.

Abrasion Resistance. Superior abrasion resistance is the major reason for the selection of cemented carbides in a wide variety of industrial applications. Most producers of cemented carbides use a wet-sand abrasion test to measure abrasion resistance. In this test, a sample is held against a rotating wheel for a fixed number of revolutions while the sample and wheel are immersed in a water slurry containing aluminum oxide particles. Comparative rankings are reported, usually on the basis of a wear rating based on the reciprocal of volume loss. Although standard test procedures are available (e.g., ASTM test 611), carbide producers have not agreed on a single test method, and so the values of abrasion resistance cited in the literature vary widely. Because of this variance, it is almost impossible to make a valid comparison among test results reported by different producers. It is also fallacious to use abrasion resistance as a measure of the wear resistance of cemented carbide materials when they are used for cutting steel or other materials; abrasion resistance in a standard test does *not* correspond directly to wear resistance in machining operations.

Generally, the abrasion resistance of cemented carbides decreases as cobalt content or grain size is increased. Abrasion resistance is also lower for complex carbides than for straight WC grades having the same cobalt content. Values of comparative abrasion resistance are listed in Table 1.

Toughness. Cemented carbides are brittle materials; usually they show less than 0.2% elongation in a tensile test.

Values of Charpy impact strength for cemented carbides have little significance and may be misleading. The energy absorbed during impact testing of very hard materials consists mainly of energy absorbed in elastic bending of the specimen and energy absorbed by the testing machine. The portion of total absorbed energy that is a measure of the toughness of a material--namely, the energy of plastic work and the energy necessary to create new surfaces--is only a few percent of the total energy measured.

Fracture toughness (K_{Ic}) values indicate the resistance of a material to fracture from intrinsic flaws. A variety of test methods and specimen geometries are used, so caution must be exercised when comparing reported values from different manufacturers. Fracture toughness increased with both increased cobalt content or WC grain size.

Corrosion resistance is not typically thought of as a requirement for carbides, and in terms of straight corrosion resistance, there are commercially available materials that are clearly superior. However, when a combination of corrosion resistance, wear resistance, stiffness, toughness, and thermal conductivity is required--such as for rotary mechanical seals in industrial pumps--cemented carbides are the material of choice.

The corrosion resistance of carbides is limited by the susceptibility of the cobalt binder to chemical attack, although there are some corrosive media that attack WC (e.g., nitric acid and hydrochloric acid). The corrosive media typically dissolve the cobalt binder from the matrix, leaving behind a weak, unsupported skeleton of WC grains, which are easily abraded away. The corrosion resistance of straight WC-Co alloys is, in general, inversely related to that of the binder content. The straight substitution of nickel binder for cobalt does provide limited improvement in both corrosion and oxidation resistance. Nickel, however, does not have the WC wettability exhibited by cobalt binders, and nickel-bonded grades have decreased hardness and toughness values relative to cobalt grades at identical binder levels. There are several grades available that utilize chromium additions to the cobalt binder to improve corrosion resistance. Chromium, however, promotes the formation of carbon-deficient ηphase with a resultant decrease in toughness and strength. The development of nickel binder grades alloyed with chromium, molybdenum, and other elements has resulted in a significant improvement in corrosion resistance.

The WC-Co cemented carbides are reasonably resistant to oxidation in air up to about 650 to 700 °C (1200 to 1290 °F). The constituent affected the fastest is WC, which will oxidize to WO_3. In oxygen, the temperature limit is lower, and rapid deterioration occurs at about 500 °C (930 °F). Even in air, however, the practical temperature limit for WC-Co compositions for any length of time is 500 to 600 °C (930 to 1110 °F). The addition of TiC or TaC to the base WC-Co composition increases the oxidation resistance somewhat.

Coated Cemented Carbides

Physical or chemical vapor deposition (PVD or CVD) are now used on the majority of metal-cutting inserts and on some wear parts. The coatings are on the order of 5 μm thick and consist of TiC, TiN, Ti(C,N), HfN, AlO, aluminum oxide, or a combination thereof (multilayer coatings). Their purpose is to minimize the wear process during steel machining; in particular, to minimize the dissolution of the workpiece material into the cutting tool, which leads to crater wear. Titanium nitride coatings are also purported to reduce the frictional forces at the tool/workpiece interface.

The methods of application for CVD and PVD coatings differ substantially. The CVD coatings are normally applied at temperatures of about 1000 °C (1830 °F) and as a result contain higher levels of residual stresses due to the difference in both thermal expansion coefficients and elastic moduli between the substrate and the coating. This results in a significant decrease (30%) in transverse-rupture strength of coated parts compared to uncoated parts. The residual tensile stresses in CVD coatings can also produce transverse cracks in the coating(s). While these cracks do not affect coating adhesion, they may initiate tool fracture in interrupted cutting operations in which the cutting edge is subjected to fatigue-type loading. One solution to the problem of coating-related tool fracture is to improve the fracture toughness of the substrate by increasing its peripheral cobalt content (cobalt enrichment). The cobalt-enriched surface zone, which is 10 to 40 μm thick, provides superior edge strength while maintaining the diffusion wear resistance of the coating layers. An example of a multiple-layer coating applied to a cobalt-enriched complex grade substrate is shown in Fig. 3.

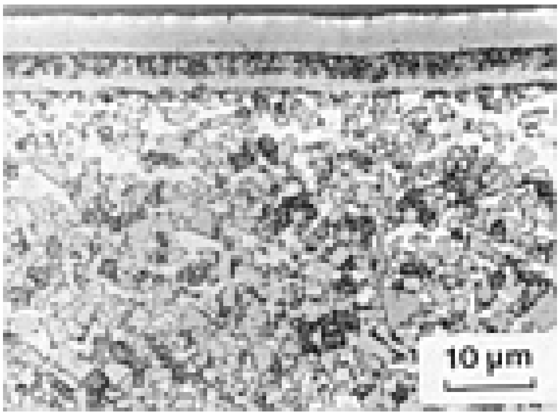

Fig. 3 Multilayer CVD coating (TiC/Ti(C,N)/TiN) on a cobalt-enriched 86WC-8(Ti,Ta,Nb)-6Co substrate. Note increased cobalt content (white constituent) at the substrate surface.

The PVD process is applied at less than 500 °C (930 °F) and results in reduced stresses in the coating and minimizes any loss in strength. A disadvantage of the PVD process is that it is a line-of-sight deposition technique. This necessitates moving the tool fixtures during the PVD deposition to ensure uniformly thick coatings on both the rake and flank faces of tool inserts.

Plasma-Assisted CVD Coatings. A compromise between the CVD and PVD techniques is the plasma-assisted CVD coating process, which offers a combination of moderate deposition temperature (~600 °C, or 1110 °F) and good thickness uniformity without the need to rotate the tools during the coating process. Both conducting (TiN and TiC) and insulating (Al_2O_3) coatings are applied using this technique.

CVD/PVD Coatings. A recent development in carbide cutting tool coatings combines an outer PVD TiN layer with inner CVD TiN/Ti(C,N) layers on a tough cobalt-enriched substrate for interrupted cutting applications such as milling. The inner CVD layers provide excellent adhesion and wear resistance, and the outer PVD layer offers a hard, fine-grain, crack-free, smooth surface endowed with compressive residual stress.

Diamond Coatings. The most recent addition to the development of hard coatings is the low-pressure synthesis of diamond films by carbonaceous gas decomposition in the presence of hydrogen ions. This process is an alternative to the high-pressure, high-temperature synthesis of bulk diamond, which is used to fabricate polycrystalline diamond (PCD). Diamond-coated carbides are used to machine aluminum-silicon alloys and nonmetallic composite materials.

Cemented Carbides for Nonmachining Applications

Almost 50% of the total production of cemented carbides is now used for nonmetal cutting applications such as metalforming dies, punches, and rolls, transportation and construction, mining, oil and gas drilling, forestry tools, and fluid-handling components. The majority of cemented carbides used for nonmachining applications are uncoated, straight WC-Co grades. Alloyed (complex) grades are used in only specialized applications. Examples of typical applications are shown in Table 4.

Table 4 Nominal composition and properties of representative cemented carbides used for nonmachining applications

Typical application	Binder content, wt%	Grain size	Hardness, HRA
Heavy blanking punches and dies, cold heading dies	20-30	Medium	85
Heading dies (severe impact), hot-forming dies, swaging dies	11-25	Medium to coarse	84
Back extrusion punches, hot-forming punches	11-15	Medium	88
Back extrusion punches, blanking punches, and dies for high shear strength steel	10-12	Fine to medium	89
Powder compacting dies, Sendzimir rolls, strip-flattening rolls, wire-flattening rolls	6	Fine	92
Extrusion dies (low impact), light blanking dies	10-12	Fine to medium	90
Extrusion dies (medium impact), blanking dies, slitters	12-16	Medium	88
Corrosion-resistant grades, valves and nozzles, rotary seals, bearings	6-12	Fine to medium	92
Corrosion-resistant grade with good impact resistance for valves and nozzles, rotary seals, and bearings	6-10 Ni	Medium	90
Deep draw dies (nongalling), tube sizing mandrels	10 Co with TiC and TaC	Medium	91

Cermets

Machining Grades. Cermets used for machining applications include TiCs and Ti(C,N)s with nickel or nickel-molybdenum binders. The manufacture of TiC/Ti(C,N) cermets is carried out with P/M methods, including liquid-phase sintering, similar to those applied for conventional carbides. As with cemented carbides, the cermet microstructures show hard, wear-resistant particles embedded in a ductile binder phase. Although the hardness at room and elevated temperatures of these materials are comparable to those of cemented carbides, their density, strength, and toughness are somewhat lower than conventional cemented carbides. Properties vary with the proportion of binder in the overall composition. In general, the corrosion resistance of TiC- and Ti(C,N)-base cermets is superior to WC-base carbides. Cermets have clearly superior oxidation resistance when compared to cemented carbides and can be used at temperatures up to 900 °C (1650 °F).

The first cutting tool in the cermet family, a TiC-Ni alloy, was commercialized as early as the 1930s, but it could not compete with the inherently stronger WC-Co-base tools. Additions of molybdenum to TiC alloys in 1960 brought cermets closer in performance to WC-Co-base tools in finish machining of steels.

Titanium carbonitride cermets based on Ti(C,N)-Ni-Mo were introduced in 1970, followed by (TiMo)(C,N)-base compositions that provided a balance of wear resistance and toughness due to their finer microstructures. Continued development in this area has now resulted in complex cermets having a variety of additives, such as Mo_2C, TaC, NbC, ZrC, HfC, WC, VC, Cr_3C_2, and aluminum. Various mixes of these additives impart different combinations of wear resistance, thermal shock resistance, and toughness, and they allow tools to be tailored for a wide range of machining applications. The newer cermets are used in semifinishing and finishing of carbon and alloy steels, stainless steels, ductile irons, free-machining aluminum and other nonferrous alloys, and some high-temperature alloys. The metal removal operations may include turning, boring, milling, threading, and grooving. Coatings (e.g., TiN) can be applied to cermet tools by the PVD process.

Steel-bonded carbides are P/M materials that are intermediate in wear resistance between tool steels and cemented carbides based on WC-Co. They consist of 25 to 45 vol% TiC homogeneously dispersed in a steel matrix. Matrices include tool steels, maraging steels, and martensitic stainless steels.

Steel-bonded TiCs respond to heat treatment and are machinable by conventional methods when the binder is in the annealed condition. Fully hardened steel-bonded carbides can be tempered at varying temperatures, thereby obtaining greater toughness than WC-Co. However, this gain in toughness is accompanied by some sacrifice in hardness. Steel-bonded carbides consisting of 45 vol% TiC have about one-half the density of the available grades of WC-Co. This is an important consideration when designing wear-resistant components for astronautical or aeronautical vehicles or for high-velocity rotating equipment.

Steel-bonded carbides are not recommended for cutting tools because the hardness drops off rapidly at the high temperatures developed during machining. They are, however, used for a variety of nonmachining wear-resistant applications such as warm and hot metalworking tools and dies.

Magnetically Soft Materials

Introduction

MAGNETIC MATERIALS are broadly classified into two groups with either hard or soft magnetic characteristics. Hard magnetic materials are characterized by retaining a large amount of residual magnetism after exposure to a strong magnetic field. These materials typically have coercive force, H_c, values of several hundred to several thousand oersteds (Oe), and are considered to be permanent magnets. The coercive force is a measure of the magnetizing force required to reduce the magnetic induction to zero after the material has been magnetized. In contrast, soft magnetic materials become magnetized by relatively low-strength magnetic fields, and when the applied field is removed, they return to a state of relatively low residual magnetism. Soft magnetic materials typically exhibit coercive force values of approximately 400 $A \cdot m^{-1}$ (5 Oe) to as low as 0.16 $A \cdot m^{-1}$ (0.002 Oe). Soft magnetic behavior is essential in any application involving changing electromagnetic induction such as solenoids, relays, motors, generators, transformers, magnetic shielding, and so on.

Important characteristics of magnetically soft materials include: (a) high permeability, (b) high saturation induction, (c) low hysteresis-energy loss, (d) low eddy-current loss in alternating flux applications, and (e) constant permeability at low field strengths and/or a minimum or definite change in permeability with temperature. Cost, availability, strength, corrosion resistance, and ease of processing are several other factors that influence the final selection of a soft magnetic material.

Magnetically soft materials manufactured in large quantities include high-purity iron, low-carbon irons, silicon (electrical) steels, nickel-iron alloys, iron-cobalt alloys, ferritic stainless steels, and ferrites (ceramics). Soft magnetic amorphous materials are being produced commercially; their characteristics are also covered in this article.

Ferromagnetic Properties

The ferromagnetic and electrical properties of materials can be divided into two general categories: those that are structure sensitive and those that are structure insensitive. Structure insensitive refers to properties not markedly affected by small changes in gross composition, small amounts of certain impurities, heat treatment, or plastic deformation. Several generally accepted structure-insensitive properties are the saturation induction (B_s), resistivity (ρ), and Curie temperature (T_c). These properties are largely dependent on the composition of the alloy selected and are not changed substantially in the process of manufacturing a component from the alloy.

Structure-sensitive properties are those drastically affected by impurities: residual strain, grain size, and so on. Permeability (μ), coercive force (H_c), hysteresis losses (W_h), residual induction (B_r), and magnetic stability are all considered to be structure sensitive. A means of controlling structure-sensitive properties is through manufacturing processing of the alloy and/or by the proper use of a final annealing heat treatment.

Effect of Impurities. Elements such as carbon, oxygen, nitrogen, and sulfur are commonly found as impurities in all alloys. Even in very low concentrations these elements tend to locate at interstitial sites in the crystalline lattice; thus, the lattice can be severely strained. Very minor concentrations can interfere with the easy movement of magnetic domains and impair soft magnetic properties. Figure 1 shows the approximate relationship between carbon content and the hysteresis loss of iron. Hysteresis losses are similarly related to sulfur and oxygen content. Furthermore, if carbon and/or nitrogen remains in the alloy uncombined, or if these elements exceed their respective solubility limits near room temperature, they can migrate in time and precipitate in a form of fine particles that can pin the magnetic domain walls. This causes a hardening of the magnetic properties known as aging.

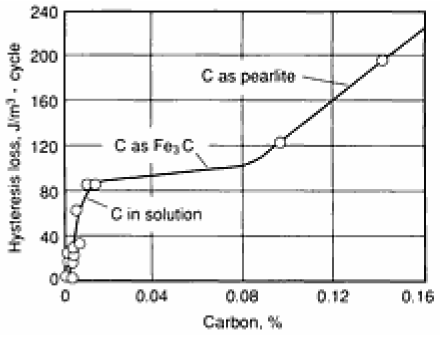

Fig. 1 Relationship between carbon content and hysteresis loss for unalloyed iron. Induction *B* = 1 T (10 kG).

Steel producers utilize raw materials and melting methods that provide impurity levels for those alloys guaranteed to provide a certain level of magnetic performance. Annealing of the fine part further reduces impurities, particularly carbon and sulfur, below the levels that can be achieved by melting control alone. In iron alloys and silicon steels, the content of the finished part should be less than 0.003% C to optimize soft magnetic properties and minimize aging.

Alloying Effects. The major constituents of most soft magnetic alloys are one or more of the common ferromagnetic elements: iron, nickel, or cobalt. Most useful combinations of these elements contribute to the control of crystalline lattice structure to promote high permeability, low coercive force, and low hysteresis loss.

Certain alloying additions can also increase electrical resistivity that helps to reduce eddy-current losses in alternating current (ac) devices. For example, pure iron can exhibit good soft magnetic properties and has a high saturation induction. It is used extensively in direct current (dc) applications and small fractional horsepower motors; however, its low electrical resistivity results in high eddy-current losses in ac applications. Figure 2 shows the changes in resistivity that result from additions of various elements to iron.

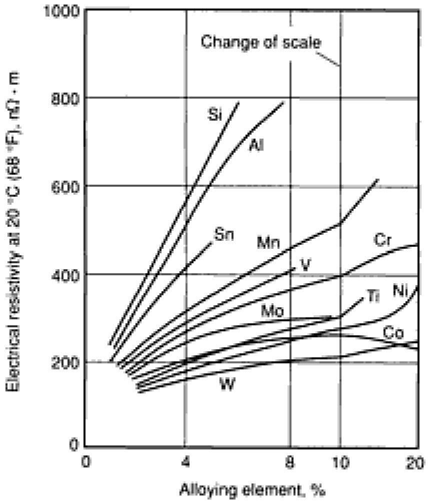

Fig. 2 Effect of alloying elements on electrical resistivity of iron

Addition of silicon in sufficient amounts eliminates the allotropic transformation in iron. Consequently, silicon-iron can be annealed at high temperature to promote grain growth, thus facilitating development of preferred grain orientation. However, room-temperature saturation induction is reduced by alloy additions other than cobalt (see Fig. 3).

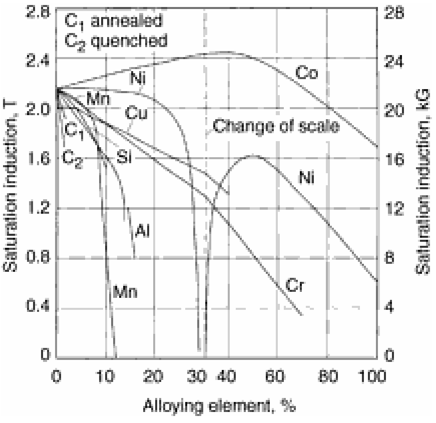

Fig. 3 Effect of alloying elements on room-temperature saturation induction of iron

Effects of Heat Treatment. Magnetic materials such as iron-nickel alloys in the cold-rolled condition must be annealed to develop the desired grain structure and magnetic properties.

Annealing conditions required for silicon steels depend on processing carried out by the supplier and on cost-versus-performance factors. Semi-processed grades must be annealed near 840 °C (1550 °F), after stamping of laminations, for removal of carbon and development of magnetic properties. Fully processed grades of non-oriented or grain-oriented steels require annealing in the range 750 to 875 °C (1375 to 1600 °F) only for removal of fabrication stresses. For wide laminations used in a flat condition, as in large power transformers, low-stress strip requiring no annealing is available.

Effects of Grain Size. For most applications, grain size should be as large as possible for nonoriented materials (Fig. 4). In oriented grades of silicon steel, optimum magnetic properties are usually obtained with grain sizes of 2 to 10 mm depending on the degree of crystal orientation: increases in grain size above 10 mm are accompanied by significant increases in both domain-wall spacing and eddy-current losses.

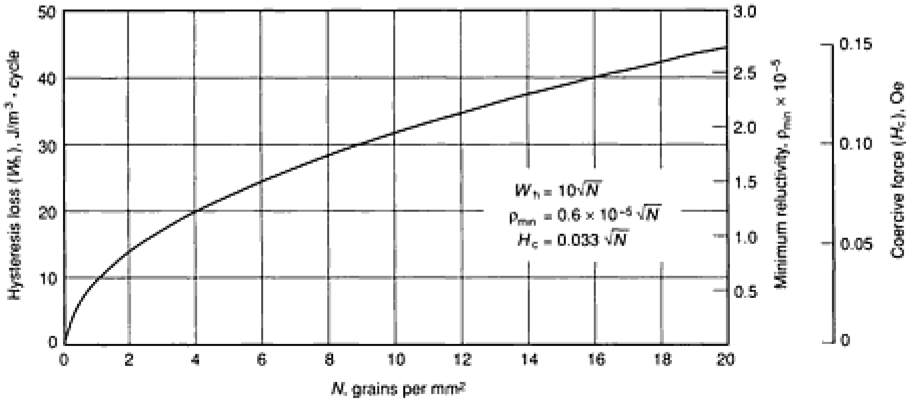

Fig. 4 Relationship between grain size and hysteresis loss for high-purity iron at B = 1 T (10 kG)

Effects of Grain Orientation. All ferromagnetic crystals are magnetically anisotropic--that is, they have different magnetic properties in different crystallographic directions. In nickel, the direction of easiest magnetization is the cube diagonal <111>; in iron it is the cube edge <100>. Crystal orientation, therefore, is a basic factor in the determination and control of magnetic properties.

High-Purity Irons

For many years, extremely high-purity (99.99%) iron has been produced for research purposes by annealing at 1300 to 1500 °C (2370 to 2730 °F) in hydrogen for several hours. It is necessary to cool slowly from the high temperature through the γ to α transformation to produce excellent soft magnetic properties. A maximum dc permeability of greater than 10^6 for purified iron has been achieved.

The saturation induction of iron, based on a density of 7.878 g/cm^3 (0.2846 lb/in.^{3}), is reported as 2.158 T (21.58 kG). The electrical resistivity is 9.8 $\mu\Omega\cdot$ cm (59 $\Omega\cdot$ circ mil/ft) at 20 °C (68 °F), and the temperature coefficient of resistivity is 0.0065/°C (0.0036/°F).

Commercial irons with purities of 99.6 to 99.8% are available in a variety of shapes. These irons have a saturation induction of approximately 2.15 T (21.5 kG), a specific gravity of 7.86, and a resistivity of approximately 13 $\mu\Omega\cdot$ cm at 20 °C (68 °F). The as-supplied carbon content of low-carbon magnetic iron is below 0.025%, typically 0.010% or less.

Low-Carbon Steels

For applications that require less than superior magnetic properties, low-carbon steels such as 1008, 1010, 12L14, and so on, are sometimes used. Such steels are not sold to magnetic quality specifications and may show considerable variation in quality, depending on melting methods and the physical condition of the as-supplied product. Parts made from these steels will generally show improved soft magnetic characteristics if annealed as normally recommended for higher-quality, soft magnetic, low-carbon iron. The degree of improvement is not guaranteed, however, and the parts may be subject to considerable magnetic aging over time. Due to their low cost, availability, and machinability, they have been used as pole pieces in electromagnets, magnetic clutches, and other noncritically designed flux carriers.

Compressed Iron Powder

For applications in which complicated magnetic parts would otherwise require considerable machining, it can be helpful to press iron powder in a mold and sinter the part in vacuum or in a reducing atmosphere. Depending on the powder metallurgy (P/M) techniques, starting powder quality, and final part configuration, the density of finished P/M iron parts can range from 6.2 g/cm^3 (0.224 lb/in.^{3}) to virtually full density of 7.8 g/cm^3 (0.282 lb/in.^{3}). It has been shown that the magnetic properties, as well as electrical resistivity, are a function of the density of the component. Higher saturation induction, residual induction, and maximum permeability result from increased density, whereas coercive force and resistivity are lowered. Soft magnetic P/M parts, including those containing 0.45 to 0.80% P, are covered in ASTM standards A 811 and A 839.

Nonoriented Silicon Steels

Except for saturation induction, the magnetic properties of iron containing a small amount of silicon are better than those of pure iron. Few commercial steels contain more than 3.5% silicon, because at levels above 4% the steel becomes brittle and difficult to process with cold rolling methods.

The commercial grades of silicon steel in common use (0.5 to 3.5% Si) are made mostly in electric or basic-oxygen furnaces. Nonoriented grades are melted with careful control of impurities; better grades have sulfur contents of approximately 0.01% or less. Continuous casting and vacuum degassing can be employed. After hot rolling, the hot bands are annealed, pickled, and cold rolled to final thickness as continuous coils.

Semiprocessed grades of strip are not sufficiently decarburized for general use, and so decarburization and annealing to develop potential magnetic quality must be done by the user. This procedure is practical for small laminations accessible to the annealing atmosphere. Fully processed grades are strand annealed in moist hydrogen at approximately 825 °C (1520 °F) to remove carbon. The final annealing operation is very important and is carried out at a higher temperature--up to 1100 °C (2000 °F) for continuous strip--to cause grain growth and development of magnetic properties. Use of a protective atmosphere is vital. The steel frequently is coated with organic or inorganic materials after annealing, to reduce eddy currents in lamination stacks.

The vast majority of finished nonoriented silicon steel is sold in either full-width coils (860 to 1220 mm, or 34 to 48 in.) or slit-width coils, but some is sold as sheared sheets.

ASTM and AISI specify standard grades of electrical steel. The AISI designations were adopted in 1946 to eliminate the wide variety in nomenclature formerly used. When originally adopted, the AISI designation number approximated ten times the maximum core loss in watts per pound, exhibited by 29 gage samples when tested at a flux density of 1.5 T (15 kG) and a magnetic circuit frequency of 60 Hz.

More specific information is given by the present ASTM designation. A typical ASTM designation is 47S200. The first two digits of the ASTM designation indicate the thickness in mm (×100). Following these digits is a letter (C, D, F, S, G, H, or P) that indicates the material type and the respective magnetic test conditions. The last three digits provide an indication of the maximum allowable core loss in units of either (watts/kg) × 100, or (watts/lb) × 100. If the core-loss value is expressed in watts/kg, the grade designation takes the suffix M, indicating an ASTM metric standard. Several ASTM flat-rolled products specifications are written in English and metric versions, such as A 677-84 and its companion metric specification A 677M-83. Table 1 gives a general summary of the ASTM code letter designation. Refer to ASTM standard A 664 for a complete explanation of the identification practice and the conditions that apply to the test parameters. The typical relative peak permeability at 60 Hz and 1.5 T (15 kG) and typical 60 Hz root mean square (rms) excitation to produce 1.5 T (15 kG) induction are useful design parameters for the application of these materials. Best permeability at high induction is obtained in steels with lower silicon contents. Low core loss is obtained with higher silicon contents, larger grains, lower impurity levels, and thinner gages. Nonoriented silicon irons are preferred for motor laminations. Table 2 lists typical applications of electrical steel sheet and strip.

Table 1 ASTM letter code designations for electrical steel and lamination steel grades (ASTM standard A 664)

Letter code	Grade	Condition	Core loss test parameters with cyclic frequency, *f,* at 60 Hz			
			Induction, *B*		**Test specimen**	**Specimen condition**
			T	**kG**		
C	Low-carbon lamination steel	Fully	1.5	15	50/50 grain	As sheared

		processed			Epstein	
D	Low-carbon lamination steel	Semiprocessed	1.5	15	50/50 grain Epstein	Quality development annealed[(a)]
F	Nonoriented electrical steel	Fully processed	1.5	15	50/50 grain Epstein	As sheared
S	Nonoriented electrical steel	Semiprocessed	1.5	15	50/50 grain Epstein	Quality development annealed[(a)]
G	Grain-oriented electrical steel	Fully processed	1.5	15	Parallel grain Epstein	Stress-relief annealed[(b)]
H	Grain-oriented electrical steel	Fully processed	1.7	17	Parallel grain Epstein	Stress-relief annealed[(b)]
P	Grain-oriented electrical steel, high permeability	Fully processed	1.7	17	Parallel grain Epstein	Stress-relief annealed[(b)]

Note: Refer to ASTM standards for detailed information regarding test methods, heat treatments, and so on.

(a) Quality development anneal--either 790 °C (1450 °F) or 845 °C (1550 °F) soak 1 h. Temperature depends on particular grade.

(b) Stress relief anneal--usually in the range from 790 °C (1450 °F) to 845 °C (1550 °F) for 1 h

Table 2 Silicon contents, mass densities, and applications of electrical steel sheet and strip

ASTM specification	AISI type	Nominal (Si + Al) content, %	Assumed density, g/cm^3	Characteristics and applications
Lamination steel				
A 726 or A 840	. . .	0	7.85	High magnetic saturation; magnetic properties may not be guaranteed; intermittent-duty small motors
Nonoriented electrical steels				
A 677 or A 677M (fully processed) and A 683 or A 683M (semiprocessed)	M-47	1.05	7.80	Ductile, good stamping properties, good permeability at high inductions; small motors, ballasts, relays
	M-45	1.85	7.75	Good stamping properties, good permeability at moderate and high inductions, good core loss; small generators, high-efficiency, continuous-duty rotating machines, ac and dc
	M-43	2.35	7.70	

	M-36	2.65	7.70	Good permeability at low and moderate inductions, low core loss; high reactance cores, generators, stators of high-efficiency rotating machines
	M-27	2.80	7.70	
	M-22[(a)]	3.20	7.65	Excellent permeability at low inductions, lowest core loss: small power transformers, high-efficiency rotating machines
	M-19[(a)]	3.30	7.65	
	M-15[(a)]	3.50	7.65	
Oriented electrical steels				
A 876 or A 876M	M-6	3.15	7.65	Grain-oriented steel has highly directional magnetic properties with lowest core loss and highest permeability when flux path is parallel to rolling direction; heavier thicknesses used in power transformers, thinner thicknesses generally used in distribution transformers. Energy savings improve with lower core loss.
	M-5	3.15	7.65	
	M-4	3.15	7.65	
	M-3	3.15	7.65	
High-permeability oriented steel				
. . .	. . .	2.9-3.15	7.65	Low core loss at high operating inductions

(a) ASTM A 677 only

Oriented Silicon Steels

Grain size is important in silicon steel with regard to core losses and low-flux density permeability. However, for high-flux density permeability, crystallographic orientation is a major controlling factor. Like iron, silicon steels are more easily magnetized in the direction of the cube edge, {100}.

When the silicon content in pure iron exceeds approximately $2\frac{1}{2}$%, the allotropic transformation of iron from α to γ is suppressed. The absence of this transformation allows the higher silicon-iron alloy to be fully ferritic up to the melting point. This behavior permits the manufacturer of these strip products to apply special cold-rolling and heat-treating techniques to promote secondary recrystallization in the final anneal. The processing results in a well-developed crystallographic texture with the cube edge parallel to the rolling direction {110}<001>, often referred to as the Goss or cube-on-edge orientation. Conventional-oriented (anisotropic) grades contain approximately 3.15% Si.

Around 1970, improved {110}<001> crystallographic texture was developed by modification of composition and processing. The improved high-permeability material usually contains approximately 2.9 to 3.2% Si. Conventional grain-oriented 3.15% Si steel has grains approximately 3 mm (0.12 in.) in diameter. The high-permeability silicon steel tends to have grains approximately 8 mm (0.31 in.) or larger in diameter. Ideally, grain diameter should be less than 3 mm (0.12

in.) to minimize excess eddy-current effects from domain-wall motion. Special coatings provide electrical insulation and induced tensile stresses in the steel substrate. In this case, the induced stresses lower core loss and minimize noise in transformers (Table 2).

High-grade silicon electrical steel does not age significantly as received from the mill, because its carbon content has been reduced to approximately 0.003% or less. With higher carbon contents, core loss can increase with time because of carbide precipitation. Also, silicon steel can age appreciably if not correctly heat treated in a manner that completely stabilizes its physical structure.

Iron-Aluminum Alloys

Although aluminum and silicon have similar effects on electrical resistivity and some magnetic properties of iron, aluminum is seldom substituted for silicon because of the resulting difficulties in fabrication. Aluminum is used most commonly as small (<0.5%) additions to the better grades of nonoriented silicon steel to increase electrical resistivity and thereby reduce eddy currents without impairing cold workability. Alloys of 12% Al or 16% Al and iron have high resistivity and can provide high permeability. At low flux densities, the magnetic properties of these alloys can be made to approach those of some of the low nickel-content, nickel-iron alloys.

Nickel-Iron Alloys

The effects of nickel content in nickel-iron alloys on saturation induction after annealing and on initial permeability are illustrated in Fig. 5 and 6, respectively. Various amounts of other elements, particularly molybdenum, often are added to these alloys to develop or accentuate specific characteristics.

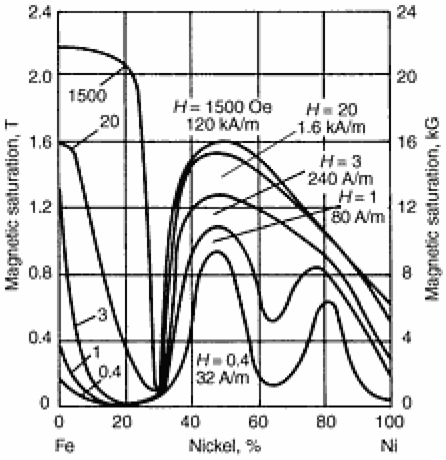

Fig. 5 Magnetic saturation of nickel-iron alloys at various field strengths. All specimens were annealed at 1000 °C (1830 °F) and cooled in the furnace.

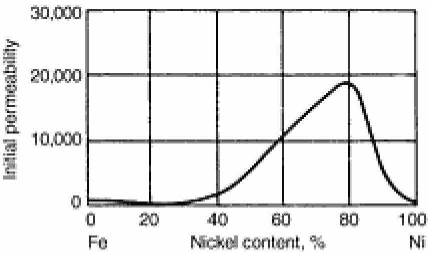

Fig. 6 Initial permeability at 2 mT (20 G) for annealed Ni-Fe alloys

In nickel-iron alloys, as in all magnetic materials, magnetic properties are controlled by saturation magnetization and magnetic anisotropy energies. Of the various types of magnetic anisotropy energy, the magnetocrystalline and magnetostrictive anisotropies are the most important in this system. Two broad classes of alloys have been developed in the nickel-iron system. The high-nickel alloys (approximately 79% Ni) have high initial permeability (Fig. 6) but low saturation induction (approximately 0.8 T, or 8 kG), whereas the low-nickel alloys (approximately 50% Ni) are lower in initial permeability but higher in saturation induction (1.5 T, or 16 kG).

The data plotted in Fig. 7 are from early laboratory studies and illustrate the effects of both composition and heat treatment on initial permeability (μ_0). Values of μ_0 above 1.2×10^4 are now obtained commercially in 50% Ni alloys, and values above 6×10^4 are obtained in 79% Ni alloys containing 4% Mo.

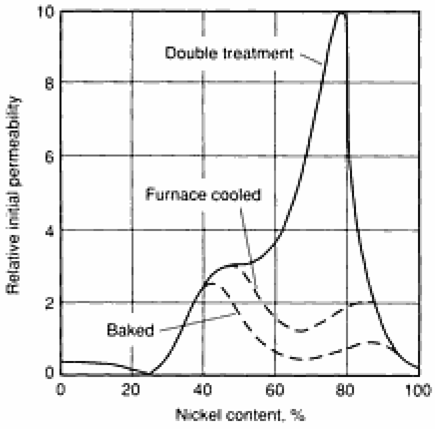

Fig. 7 Relative initial permeability at 2 mT (20 G) for nickel-iron alloys given various heat treatments. Treatments were as follows: furnace cooled--1 h at 900 to 950 °C (1650 to 1740 °F), cooled at 100 °C/h (180 °F/h); baked--furnace cooled plus 20 h at 450 °C (840 °F); double treatment--furnace cooled plus 1 h at 600 °C (1110 °F) and cooled at 1500 °C/min (2700 °F/min).

To obtain high initial permeability, both magnetocrystalline anisotropy (K_1) and magnetostrictive anisotropy (λ_s) must be minimized. Cooling rate--or, in other words, the degree of atomic ordering achieved in the critical temperature range from 760 to 315 °C (1400 to 600 °F)--has a profound influence on the ability to minimize K_1. Consequently, cooling of this alloy from heat treating temperatures must be precisely controlled to obtain $K_1 = 0$. For commercially practical cooling rates of approximately 100 °C/min (180 °F/min), optimum composition for achieving $K_1 = 0$ and $\lambda_s = 0$ is approximately 4% Mo and 80% Ni.

Because $K_1 = 0$ and $\lambda_s = 0$ for commercial alloys such as Supermalloy, Moly Permalloy, and Hymu 80, all of which contain approximately 4% Mo and 80% Ni, grain orientation is not critical for these alloys. Purity, however, influences permeability and core loss. Interstitial impurities such as carbon and nitrogen must be minimized by special melting procedures and by careful final annealing of laminations and other core configurations. Oxygen and sulfur are also objectionable. Best magnetic properties in nickel-iron alloys are obtained by annealing in pure dry hydrogen (dew point less than -50 °C, or -58 °F) at 1000 to 1200 °C (1830 to 2200 °F) for several hours to reduce carbon, nitrogen, sulfur, and oxygen contents. Sulfur contents higher than several ppm and carbon in excess of 20 ppm are detrimental to final annealed magnetic properties.

Most applications of 50% Ni alloys are based on requirements for high saturation induction. Nickel content is not critical near the middle of the iron-nickel series (50% Ni) and can be varied from 45 to 60%, but for highest saturation induction it should be held close to 50% (Fig. 5). Although $K_1 = 0$, the value of λ_{100}, which is the magnetostrictive constant in the <100> easy direction of magnetization, is close to zero for these alloys. Therefore, the initial permeability is still reasonable and in fact reaches a small maximum (Fig. 6). In some applications, such as converters, a high squareness ratio is desired--that is, a high ratio of remanence to saturation induction (B_r/B_s). In 50% Ni alloys, where the magnetocrystalline anisotropy is not zero, excellent squareness can be achieved by careful development of a cube texture during the final high-temperature anneal. In applications of nickel-iron alloys it is thus important to control magnetic anisotropy energies, purity, and texture, depending on what combination of properties is desired.

Iron-Cobalt Alloys

Pure iron has a saturation induction of 2.158 T (21.58 kG). Higher saturation values can be achieved only in alloys of iron and cobalt. The highest known value is approximately 2.46 T (24.6 kG), which occurs at a cobalt content of -35%. Use of alloys containing 25 to 50% Co is limited by low resistivity and high hysteresis loss, the high cost of cobalt and the brittleness of alloys containing more than 30% Co. However, with small additions of vanadium and special treatment in processing, 49Co-49Fe-2V alloys can be cold rolled commercially to any gage, and strip is ductile enough to be punched and sheared. The 27Co-0.6Cr-Fe alloy is more easily fabricated, and less subject to degradation by stresses, than the approximately 50% Co alloy. Furthermore, proper annealing of the 27% Co alloy produces magnetic properties suitable for both dc and ac applications. Alternating-current applications require low eddy-current and hysteresis losses. Eddy-current losses can be minimized by a proper combination of composition and thickness.

Ferritic Stainless Steels

Ferritic stainless steels have been used as soft magnetic components in products such as solenoid housings, cores, and pole pieces. Although their magnetic properties are not generally as good as conventional soft magnetic alloys, they have been successfully used for magnetic components that must withstand corrosive environments. As such, they offer a cost-effective alternative to plated iron and silicon-iron components. In addition, the relatively high electrical resistivity of ferritic stainless steels has resulted in superior ac performance.

Special restricted analyses of AISI type 430F are produced for use in solenoid valve components. The ASTM A 838 specification provides typical properties for these alloys. Alloy type I is 430F containing approximately 0.4% Si and exhibiting an electrical resistivity of 60 $\mu\Omega\cdot$ cm. When fully mill annealed, it has a hardness of approximately 78 HRB. Its maximum dc permeability is approximately 2×10^3, with a coercivity of approximately 160 $A \cdot m^{-1}$ (2 Oe). Alloy type 2 (430FR) is a higher-silicon version of 430F, with an electrical resistivity of 76 $\mu\Omega\cdot$ cm and a fully annealed hardness of 82 HRB. Despite its higher hardness, alloy type 2 typically exhibits a dc permeability of 2.6×10^3 and a coercivity of 130 $A \cdot m^{-1}$ (1.6 Oe).

Amorphous Metals

Suitable alloys prepared in amorphous, noncrystalline form (metallic glasses) have the attractive combinations of high permeability and high volume resistivity. In the preferred planar-flow casting method of production, the metal is rapidly quenched from the melt onto cooled rotating drums to form long ribbons approximately 30 to 50 μm thick and up to 1 m (40 in.) wide (Fig. 8). Alloys produced for soft magnetic applications include iron-, iron/nickel-, and cobalt base alloys containing varying amounts of metalloids (boron, silicon, carbon, and phosphorus) and other alloying elements such as chromium, molybdenum, nickel, iron, and aluminum. Examples of commonly employed compositions include:

Fe-base	**$Fe_{80}B_{20}$**
	$Fe_{80}P_{13}C_7$
	$Fe_{80}P_{16}B_1C_3$
	$Fe_{67}Co_{18}B_{14}Si_1$
	$Fe_{81}B_{13.5}Si_{2.5}C_2$
	$Fe_{76.5}Cr_2B_{16}Si_5C_{0.5}$

	$Fe_{75}Ni_4Mo_3B_{16}Si_2$
FeNi-base	$(FeNi)_{80}B_{20}$
	$(FeNi)_{80}P_{10}B_{10}$
	$Fe_{40}Ni_{38}P_{14}B_6$
	$Fe_{38.5}Ni_{38.5}P_{14}B_6Al_{1.5}Si_{1.5}$
Co-base	$Co_{72}Fe_3P_{16}B_6Al_3$

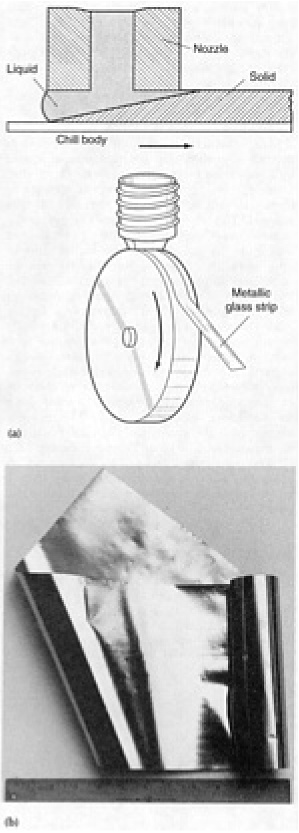

Fig. 8 Preparation of metallic glass (amorphous metal) strip. (a) Schematic of the planar-flow casting method. The arrow indicates the direction of the material flow, which is identical to the direction of the chill wheel rotation. (b) Sheet of metallic glass prepared by the planar-flow casting process, which is used to wind power-distribution transformer cores

These materials are characterized by low hysteresis loss and low coercive force. However, Curie temperature is limited to approximately 475 °C (900 °F), and magnetic saturation is limited to approximately 1.7 T (16 kG). Figure 9 compares the magnetic properties of amorphous metals and conventional crystalline soft magnetic materials.

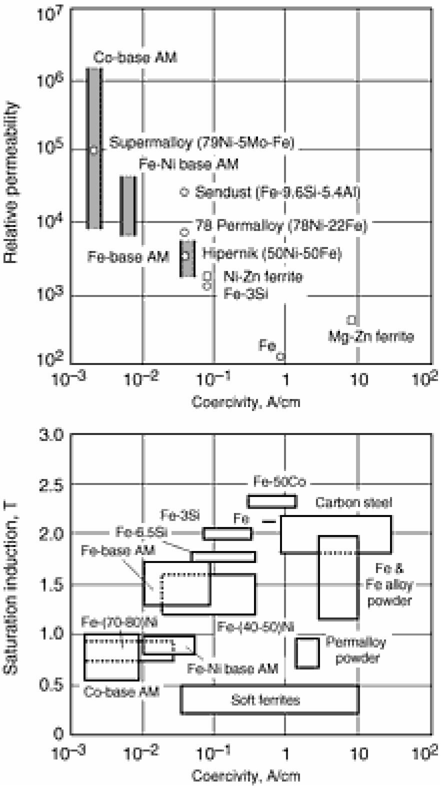

Fig. 9 Saturation induction and relative permeability versus coercivity for commercial available amorphous metals (AM) and crystalline soft ferromagnets. Permeabilities for amorphous metal depend on heat treatments and are indicated by shaded bars.

The innovation of the planar flow casting method for producing uniform sheets of metallic glass has resulted in the commercialization of metallic glasses as a core material for power-distribution transformers. Distribution transformers are used by the utility companies in the final voltage step down in the network that supplies power to residences, stores, offices, and small industries.

These transformers are put into service for a period of 25 to 40 years, and during that time the primary coil is continuously energized. The significance of this duty pattern lies in the fact that the core material in the transformer is cycled at a frequency of 50 or 60 Hz continuously during the lifetime of the transformer. During each cycle, energy is lost to the magnetic core material. In addition, the alternating field produces eddy currents and accompanying losses within the transformer. Core losses are essentially determined by the coercive force, whereas the eddy current losses are proportional to the electrical conductivity of the material and inversely proportional to the thickness of the individual sheets of magnetic material from which the core is wound.

The low electrical conductivity of metallic glasses compared with conventional crystalline core materials (grain-oriented silicon steels) makes amorphous metals extremely attractive for reducing eddy current losses. The low coercive forces compared with competing crystalline materials reduce core loss (core losses of amorphous metal distribution transformers are approximately $\frac{1}{3}$ to $\frac{1}{6}$ those of silicon steels). Taken together with the fact that the continuous planar flow casting process leads to low fabrication costs, these features have led to the introduction of metallic glasses into the commercial transformer core market. The use of amorphous metals in this application can reduce energy losses, thereby reducing costs.

Ferrites

Ferrites for high-frequency applications are ceramics with characteristic spinel-magnetic structures ($M \cdot Fe_2O_4$, where M is a metal) and usually comprise solid solutions of iron oxide and one or more oxides of other metals such as manganese, zinc, magnesium, copper, nickel, and cobalt. They are unique among magnetic materials in their outstanding magnetic properties at high frequencies, which result from very high resistivities ranging from approximately $10^8\ \Omega \cdot$ cm to as high as 10^{14} $\Omega \cdot$ cm. Hence, at frequencies where eddy-current losses for metals become excessive, ferrites make ideal soft magnetic materials. Because ferrites have inherently high corrosion resistance, parts made of these materials normally do not require protective finishing.

Disadvantages of ferrites include low magnetic saturation, low Curie temperature, and relatively poor mechanical properties compared with those of metals. Ferrites are produced from powdered raw materials by mixing, calcining, ball milling, pressing to shape, and firing to the desired magnetic properties. The final product is hard, brittle, and unmachinable, and thus close dimensional tolerances must be obtained by grinding.

Many different ferrites are available for magnetic use. They can be classified into three general types: square-loop ferrites for computer memories, linear ferrites for transformers and for inductors in filters, and microwave ferrites for microwave devices. In recent years, due to increasing use of semiconductors for computer memories, square-loop ferrites have decreased in importance.

Microstructure and composition have much stronger influences on the magnetic properties of ferrites than on those of metals. Hence, properties of finished ferrite parts can vary drastically with purity and structure of raw materials, with the nature of binders used, and with the ceramic-processing technique employed. In general, lithium ferrites, Mn-Mg-Zn ferrites, and Mn-Mg-Di ferrites are used for computer memories. (Di is the symbol for didymium, a mixture of the rare earth elements praseodymium and neodymium.) Lithium ferrite is higher in Curie temperature and saturation magnetization, but lower in switching speed, than Mn-Mg-Zn and Mn-Mg-Di ferrites. Linear ferrites comprise manganese-zinc and nickel-zinc ferrites. Manganese-zinc ferrite is higher in saturation magnetization, but lower in resistivity, than nickel-zinc ferrite. Manganese-zinc ferrite is preferred for frequencies up to approximately 1 MHz. For microwave applications, Ni-Zn, Mg-Mn-Al, and Mg-Mn-Cu ferrites are used, as well as garnets of the type $M_{3+x}Fe_{5-x}O_{12}$ (where M = Y + Al, or M = Y + Gd + Al).

Constant Permeability with Changing Temperature

In all magnetic materials, magnetic properties change with temperature. Proper selection and preparation of materials, and proper circuit design, can minimize these changes.

Change in flux density with temperature for iron tested at four different values of magnetizing force is plotted in Fig. 10. Operation of a device at a flux density of 1.5 T (15 kG) would be only slightly affected by variations in operating temperature near ambient. There is a similar minimized temperature effect for all materials, except that the flux density for optimum operation depends on the materials, given the proper flux density and temperature range. Great changes occur at temperatures approaching the Curie temperature (Fig. 10).

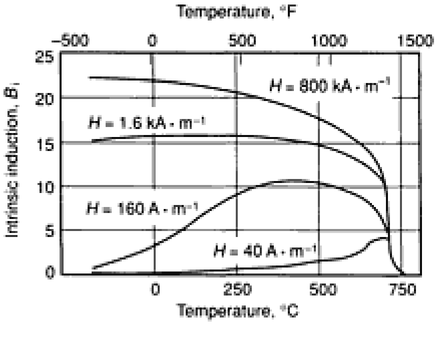

Fig. 10 Variation of induction with temperature for iron, at four different values of magnetizing force

For many reasons, it is not always possible to operate a material at the best flux density for temperature stability. One way of obtaining better temperature stability is to use magnetic materials in insulated powder form, such as pressed Permalloy powder cores, which have good temperature stability due to the presence of many built-in air gaps. Another method involves use of nickel-iron alloys, such as Isoperm or Conpernik, that have been drastically cold rolled and then underannealed to produce a partly strained alloy less sensitive to temperature changes.

In a third method, two alloy powders with opposite temperature coefficients are combined for use in the desired temperature range. Special Permalloy powder cores are combined with small amounts of Ni-Fe-Mo powder having a low Curie temperature and a negative temperature coefficient near room temperature. The 30% Ni irons are of the low-Curie-temperature type.

Alloys for Magnetic Temperature Compensation

Many measuring instruments and other devices depend on maintaining constant flux, produced by a permanent magnet, across an air gap. Unfortunately, as a permanent magnet is warmed, it loses strength and the air gap flux density changes. To compensate for such changes, a certain amount of the magnetic flux can be shunted around the air gap of the instrument by using an alloy with high negative magnetic temperature coefficient in the temperature range of interest. The amount of shunted flux, therefore, decreases with increasing ambient temperature, forcing more flux through the gap than would normally occur. Nearly complete compensation for temperature changes can be made by correct design of parts. Watt-hour meters and automobile speedometers are examples in which a temperature compensator shunt has been used to compensate for the change in pole strength of the permanent magnet (and the change in electrical resistivity of the aluminum drag disk) over their designed working-temperature range. Nickel-iron alloys containing between approximately 28% and 36% Ni are frequently used commercially for this purpose.

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Permanent Magnet Materials

Introduction

PERMANENT MAGNET is the term used to describe solid materials that have sufficiently high resistance to demagnetizing fields and sufficiently high magnetic flux output to provide useful and stable magnetic fields. Permanent magnets are normally used in a single magnetic state. This implies insensitivity to temperature effects, mechanical shock, and demagnetizing fields. This article does not consider magnetic memory or recording materials in which the magnetic state is altered during use. It does include, however, hysteresis alloys used in motors.

Permanent magnet materials include a variety of alloys, intermetallics, and ceramics. Commonly included are certain steels, Alnico (a cast or sintered iron-base alloy containing 7 to 10% Al, 15 to 19% Ni, 13 to 35% Co, 3 to 4% Cu, with an optional 1 to 5% Ti), Cunife (60Cu-20Ni-20Fe), iron-cobalt containing vanadium or chromium, platinum-cobalt, hard ferrites ($SrO\text{-}Fe_2O_3$ or $BaO\text{-}6Fe_2O_3$), cobalt-rare earth alloys ($SmCo_5$ or SM_2CO_{17}), and neodymium-iron-boron alloys made by powder metallurgy processing. Each type of magnet material possesses unique magnetic and mechanical properties, corrosion resistance, temperature sensitivity, fabrication limitations, and cost. These factors provide designers with a wide range of options in designing magnetic parts.

Permanent magnet materials are based on the cooperation of atomic and molecular moments within a magnet body to produce a high magnetic induction. This induced magnetization is retained because of a strong resistance to demagnetization. These materials are classified ferromagnetic or ferrimagnetic and do not include diamagnetic or paramagnetic materials. The natural ferromagnetic elements are iron, nickel, and cobalt. Other elements, such as manganese or chromium, can be made ferromagnetic by alloying to induce proper atomic spacing. Ferromagnetic metals combine with other metals or with oxides to form ferrimagnetic substances; ceramic magnets are of this type. Although scientific literature lists many magnetic substances, relatively few have gained commercial acceptance because of the commercial requirement for low cost and high efficiency.

Permanent magnet materials are developed for their chief magnetic characteristics: high induction, high resistance to demagnetization, and maximum energy content. Magnetic induction is limited by composition; the highest saturation induction is found in binary iron-cobalt alloys. Resistance to demagnetization is conditioned less by composition than by shape or crystal anisotropies and the mechanisms that subdivide materials into microscopic regions. Precipitations, strains and other material imperfections, and fine particle technology are all used to obtain a characteristic resistance to demagnetization.

Maximum energy content is most important because permanent magnets are used primarily to produce a magnetic flux field (which is a form of potential energy). Maximum energy content and certain other characteristics of materials used for magnets, are best described by its hysteresis loop. Hysteresis is measured by successively applying magnetizing and demagnetizing fields to a sample and observing the related magnetic induction.

Fundamentals of Magnetism

For understanding a permanent magnet, Faraday's concept of representing a magnetic flux field by lines of force is very useful. The lines of force radiate outward from a north pole and return at a south pole. The lines of force can be revealed by a powder pattern made by sprinkling iron powder on a paper placed above a bar magnet. The number of lines per unit area is the magnetic induction and is designated B. Induction in the magnet consists of lines of force due to the magnetic field and lines of magnetization due to the ferromagnetism of the magnet:

$$B = H + B_i \qquad \textbf{(Eq 1)}$$

where H is the magnetic field strength and B_i is the intrinsic induction.

Magnetic Hysteresis. A hysteresis loop is a common method of characterizing a permanent magnet. The intrinsic induction is measured as the magnetizing field is changed (see Fig. 1). Starting with a virgin state of the material at the origin 0, induction increases along curve I to the point marked +S as the field is increased from zero to maximum. The point +S is the point at which induction no longer increases with higher magnetizing field, and is known as the saturation induction. When the magnetizing field is reduced to zero in permanent magnets, most of the induction is retained. In Fig. 1, when the field is reduced through zero and reversed to -S, the induction decreases from +S to B_r to -S. At zero field, there is a remanent magnetization in the sample, defined as B_r; the value of B_r approaches the saturation induction in well prepared permanent magnet materials. This point on the hysteresis loop is called residual induction.

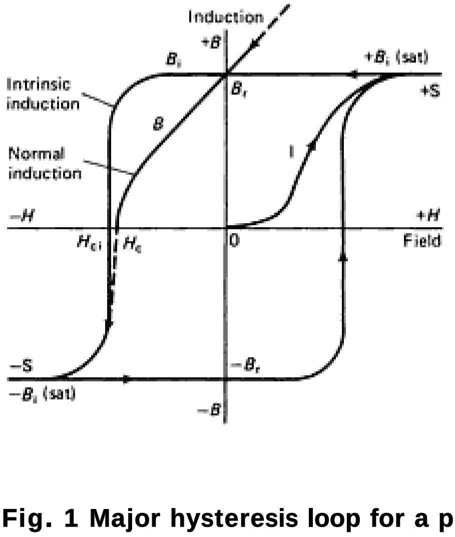

Fig. 1 Major hysteresis loop for a permanent magnet material. B_i (sat) is the saturation induction

If the field is increased again in the positive direction, the induction passes through -B_r to +S as shown, and not through the origin. Thus, there is a hysteresis effect, and this plot is called the hysteresis loop. The two halves of the loop are generally symmetrical and form a major loop, which represents the maximum energy content, or the amount of magnetic energy that can be stored in the material. Innumerable minor loops can be measured within the major loop, measurements being made to show the effects of lesser fields on magnets under operating conditions.

Demagnetization. The particular value of the demagnetizing field needed to reduce B_i, (or J) to zero is called the intrinsic coercive force H_{ci}. Figure 1 includes the normal demagnetization curve derived from the intrinsic curve. The field required to reduce induction B to zero is the normal coercive force H_c. The important practical features of the curve for application to permanent magnet materials are the numerical values of B_r, H_c, H_{ci}, and the area within the hysteresis loop.

Because a permanent magnet most often is used to provide a flux field in a space outside itself, the material rests within its own field, which is a self-demagnetizing field. Therefore, for practical applications, a magnet designer is interested primarily in the second quadrant of the hysteresis loop, called the demagnetization curve (see Fig. 2). This curve represents the resistance to demagnetization and, in an affirmative sense, the ability of a material to establish a magnetic field in an air gap or adjoining magnetic material.

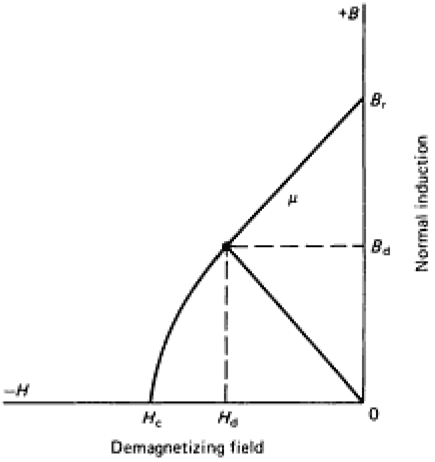

Fig. 2 Normal demagnetization curve for a permanent magnet material

Magnetic Energy. The maximum magnetic energy available for use outside the magnet body is proportional to the largest rectangle that fits inside the normal demagnetization curve. It is indicated by the product $(B_dH_d)_{max}$, and is usually cited as the figure if merit for determining the quality of permanent magnet materials.

A characteristic useful in selecting permanent magnet materials subjected to varying demagnetizing conditions is the permeability (that is, the ratio of the induction to the corresponding magnetizing force) at the operating point:

$$\mu = B_d/H_d \qquad \textbf{(Eq 2)}$$

For example, a straight-line demagnetization curve where $B_r = H_c$ would have the ideal permeability of 1.0; a magnet of such a material would recover spontaneously all flux when a partial demagnetizing field is removed. The corresponding intrinsic curve would be flat out to the knee, and the material would retain maximum energy. Rare-earth alloys and high coercivity hard ferrite magnets come closest to ideal permanent magnet behavior.

Figure 3 is the product curve of B and H at each point along the demagnetization curve, plotted against B. On the demagnetization curve, each value of B or H involves the other as a coordinate variable. The maximum value of their product--$(B_dH_d)_{max}$--represents the maximum magnetic energy that a unit volume of the material can produce in an air gap. Often, the most efficient design for a magnet is that which employs the magnet at the flux density corresponding to the $(B_dH_d)_{max}$ value.

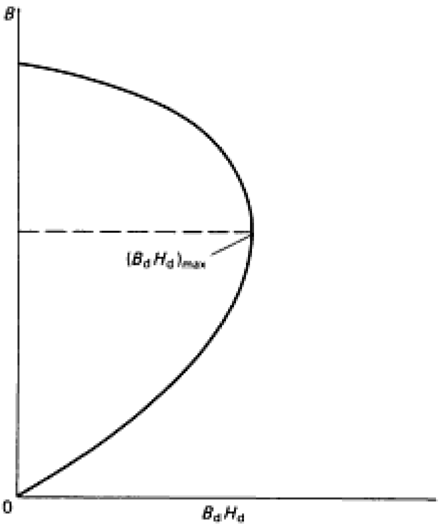

Fig. 3 Typical energy-product curve for a permanent magnet material

The amount of total external magnetic flux available from a magnet operating in an open-circuit condition (that is, some flux both in air or nonmagnetic substance) depends on its shape. Figure 4 shows this relation for one specific shape. The permeability μ is the ratio of the total external permeance B_d to that of the permeance of the space occupied by the magnet, H_d, and is equal to the slope of the demagnetization curve.

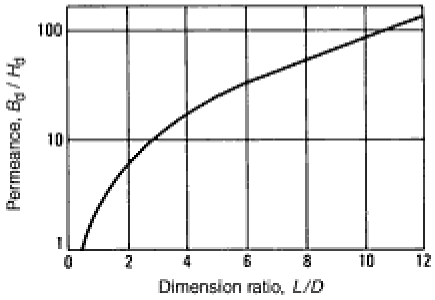

Fig. 4 Relation between magnetic properties and dimensions of straight bar magnets of circular cross section

Figure 5 gives an enlarged plot of the first and second quadrants of the intrinsic induction curve. The intrinsic demagnetization curve is of interest to both the materials scientist and the applications engineer. Material scientists are concerned about the effect of composition and processing on the various intrinsic parameters of the material: B_{is}, B_r, and H_{ci}. Applications engineers are concerned about the flux density in an air gap due to both B_i and H. Accordingly, they are interested in the normal induction curve and in the values of B_r, H_c, and $(BH)_{max}$. Design engineers use the intrinsic induction curve to predict performance while the magnet is under the influence of temperature, armature reaction, or other demagnetizing forces.

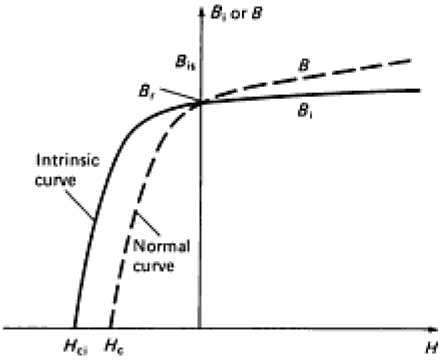

Fig. 5 Intrinsic magnetization curve B_i in the first and second quadrants compared with the curve for B

Lines of constant energy product (B_dH_d) usually are plotted in the second quadrant area of a hysteresis loop, As illustrated in Fig. 6, they appear as a series of hyperbolic curves superimposed on the rectangular *B*-*H* grid of the demagnetization curves. The maximum values of external energy are therefore readily available in relation to the demagnetization curve. In this form, the grid constitutes an efficient guide for the design engineer. In practice, a magnet with a fixed air gap would have one fixed B_d/H_d operating point on the demagnetization curve corresponding to the material being used. For variable air gaps, such as are produced by relative movement between the armature and field poles of electrical machinery, the external energy available at the air gap changes continuously, resulting in a so-called minor loop with minimum and maximum values. In practice, the minor loop is plotted on the demagnetization curve to determine location of the loop on the curve, and to evaluate the extent of flux variation within the minor loop cycle. Efficient design of equipment using permanent magnets, such as magnetos, small generators, and motors, requires that the minor loop operate near the $(B_dH_d)_{max}$ point.

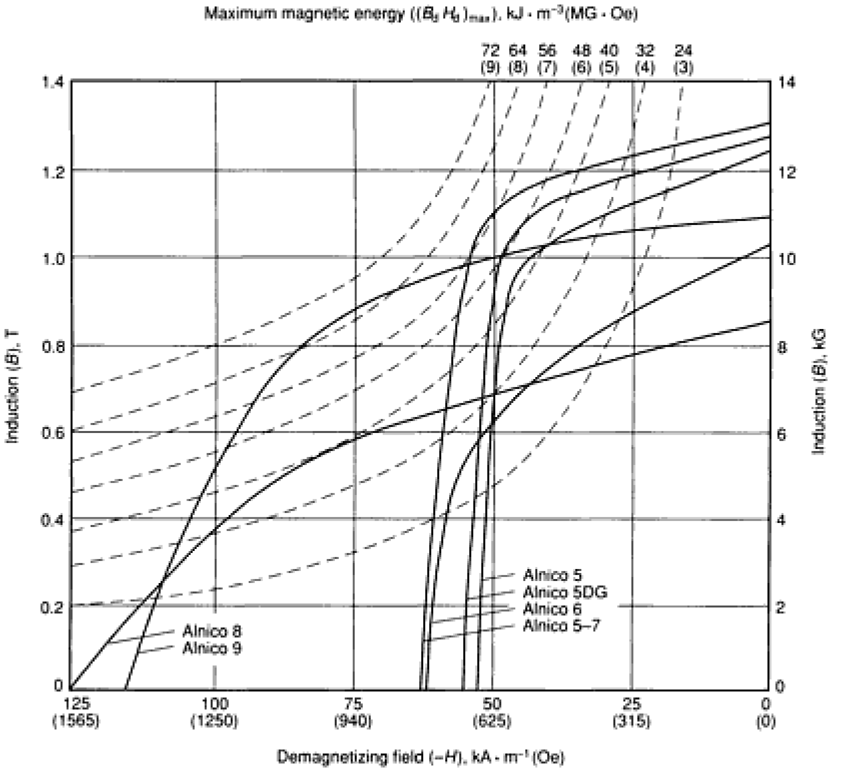

Fig. 6 Magnetization curves for anisotropic cast Alnico permanent magnet materials

Magnetically soft materials differ from permanent magnet materials not only in their higher permeabilities, but also, and more significantly, in their much lower resistance to demagnetization. The best magnetically soft materials have H_c values of virtually zero. The hysteresis loop of such a material retraces itself through or near the origin point with each cycle.

Conversely, permanent magnet materials have wide hysteresis loops, characterized by high values of H_{ci}, which range from approximately 8 to $>1.6 \times 10^3$ kA · m^{-1} (100 Oe to >20 kOe).

Permanent Magnet Materials

Compositions and Properties. Table 1 lists selected permanent magnet materials commercially available in the United States and their nominal compositions. Magnetic properties are given in Table 2. Physical and mechanical properties are summarized in Table 3. The production of permanent magnet materials is controlled to achieve magnetic characteristics, and other properties are allowed to vary according to the manufacturing process used. The selection of materials and the design of permanent magnets for particular applications is a well-defined engineering art; design assistance is available from most producers.

Table 1 Nominal compositions, Curie temperatures, and magnetic orientations of selected permanent magnet materials

Designation	Nominal composition	Approximate Curie temperature		Magnetic orientation(a)
		°C	**°F**	
$3\frac{1}{2}$ % Cr steel	Fe-3.5Cr-1C	745	1370	No
6% W steel	Fe-6W-0.5Cr-0.7C	760	1400	No
17% Co steel	Fe-17Co-8.25W-2.5Cr-0.7C	. . .	. . .	No
36% Co steel	Fe-36Co-3.75W-5.75Cr-0.8C	890	1630	No
Cast Alnico 1	Fe-12Al-21Ni-5Co-3Cu	780	1440	No
Cast Alnico 2	Fe-10Al-19Ni-13Co-3Cu	810	1490	No
Cast Alnico 3	Fe-12Al-25Ni-3Cu	760	1400	No
Cast Alnico 4	Fe-12Al-27Ni-5Co	800	1475	No
Cast Alnico 5	Fe8.5Al-14.5Ni-24Co-3Cu	900	1650	Y, H
Cast Alnico 5DG	Fe-8.5Al-14.5Ni-24Co-3Cu	900	1650	Y, H, C
Cast Alnico 5-7	Fe-8.5Al-14.5Ni-24Co-3Cu	900	1650	Y, H, C
Cast Alnico 6	Fe-8Al-16Ni-24Co-3Cu-2Ti	860	1580	Y, H
Cast Alnico 7	Fe-8Al-18Ni-24Co-4Cu-5Ti	840	1540	Y, H
Cast Alnico 8	Fe-7Al-15Ni-35Co-4Cu-5Ti	860	1580	Y, H
Cast Alnico 9	Fe-7Al-15Ni-35Co-4Cu-5Ti	. . .	. . .	Y, H, C
Cast Alnico 12	Fe-6Al-18Ni-35Co-8Ti	. . .	. . .	No
Sintered Alnico 2	Fe-10Al-17Ni-12.5Co-6Cu	610	1490	No
Sintered Alnico 4	Fe-12Al-28Ni-5Co	800	1475	No
Sintered Alnico 5	Fe-8.5Al-14.5Ni-24Co-3Cu	900	1650	Y, H
Sintered Alnico 6	Fe-8Al-16Ni-24Co-3Cu-2Ti	860	1580	Y, H
Sintered Alnico 8	Fe-7Al-15Ni-35Co-4Cu-5Ti	860	1580	Y, H
Cunife	20Fe-20Ni-60Cu	410	770	Y, R
Bonded ferrite A	BaO-6Fe$_2$O$_3$ + organics	450	. . .	No, P
Bonded ferrite B	BaO-6Fe$_2$O$_3$ + organics	450	. . .	No
Sintered ferrite 1	BaO-6Fe$_2$O$_3$	450	840	No, P
Sintered ferrite 2	BaO-6Fe$_2$O$_3$	450	840	Y, A
Sintered ferrite 3	BaO-6Fe$_2$O$_3$	450	840	Y, A
Sintered ferrite 4	SrO-6Fe$_2$O$_3$	460	860	Yes
Sintered ferrite 5	SrO-6Fe$_2$O$_3$	460	860	Yes
Bonded neodymium	NdFeB + organics	. . .	. . .	Y, P, E
Hot-formed neodymium	. . .	. . .	. . .	Y, R
Hot-pressed neodymium	NdFeB + organics	. . .	. . .	Y, R
Sintered neodymium	NdFeB	310	590	Y, A
FeCrCo	. . .	640	1185	Y, R
Platinum cobalt	76.7Pt-23.3Co	480	900	No
Cobalt rare earth 1	SmCo$_5$	725	1340	Y, A
Cobalt rare earth 2	SmCo$_5$	725	1340	Y, A
Cobalt rare earth 3	SmCo$_5$	725	1340	Y, A

Cobalt rare earth 4	Sm_2Co_{17}	800	1475	Y, A
Bonded Co rare earth	. . .	. . .	. . .	Y, P, E

(a) Y, yes; H, orientation developed during heat treatment; C, columnar crystal structure developed; P or E, some orientation developed during pressing or extrusion; R, orientation developed by rolling or other mechanical working; A, orientation developed predominately by magnetic alignment of powder prior to compacting but alignment influenced by pressing forces also

Table 2 Nominal magnetic properties of selected permanent magnet materials

Designation	H_c		H_{ci}		B_r		B_{is}		$(BH)_{max}$		B_d		H_d		Required magnetizing field		Permeance coefficient at $(BH)_{max}$	Average recoil permeability, G/Oe
	kA · m^{-1}	**Oe**	**kA · m^{-1}**	**Oe**	**T**	**kG**	**T**	**kG**	**kJ · m^{-3}**	**MG · Oe**	**T**	**kG**	**kA · m^{-1}**	**Oe**	**kA · m^{-1}**	**kOe**		
3$\frac{1}{2}$ % Cr steel	5.3	66	. . .	. . .	0.95	9.5	. . .	. . .	2.3	0.29	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6% W steel	5.9	74	. . .	. . .	0.95	9.5	. . .	. . .	2.6	0.33	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
17% Co steel	14	170	. . .	. . .	0.95	9.5	. . .	. . .	5.2	0.65	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
36% Co steel	19	240	. . .	. . .	0.975	9.75	. . .	. . .	7.4	0.93	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Cast Alnico 1	35	440	36	455	0.71	7.1	1.05	10.5	11	1.4	0.45	4.5	24	305	160	2.0	14	6.8
Cast Alnico 2	44	550	46	580	0.725	7.25	1.09	10.9	13	1.6	0.45	4.5	28	350	200	2.5	12	6.4
Cast Alnico 3	38	470	39	485	0.70	7.0	1.00	10.0	11	1.4	0.43	4.3	26	320	200	2.5	13	6.5
Cast Alnico 4	58	730	62	770	0.535	5.35	0.86	8.6	10	1.3	0.30	3.0	34	420	280	3.5	8.0	4.1
Cast Alnico 5	50	620	50	625	1.25	12.5	1.35	13.5	42	5.25	1.02	10.2	42	525	240	3.0	18	4.3
Cast Alnico 5DG	52	650	52	655	1.29	12.9	1.40	14.0	49	6.1	1.05	10.5	46	580	280	3.5	17	4.0
Cast Alnico 5-7	58	730	59	735	1.32	13.2	1.40	14.0	59	7.4	1.15	11.5	51	640	280	3.5	17	3.8
Cast Alnico 6	60	750	. . .	. . .	1.05	10.5	1.30	13.0	30	3.7	0.71	7.1	42	525	320	4.0	13	5.3
Cast Alnico 7	84	1,050	. . .	. . .	0.857	8.57	0.945	9.45	30	3.7	. . .	. . .	. . .	. . .	400	5.0	8.2	. . .
Cast Alnico 8	130	1,600	138	1,720	0.83	8.3	1.05	10.5	40	5.0	0.506	5.06	76	950	640	8.0	5.0	3.0
Cast Alnico 9	115	1,450	. . .	. . .	1.05	10.5	. . .	. . .	68	8.5	. . .	. . .	. . .	. . .	560	7.0	7.0	. . .
Cast Alnico 12	76	950	. . .	. . .	0.60	6.0	. . .	. . .	14	1.7	0.315	3.15	43	540	400	5.0	5.6	. . .
Sintered Alnico 2	42	525	44	545	0.67	6.7	1.10	11.0	12	1.5	0.43	4.3	28	345	200	2.5	12	6.4
Sintered Alnico 4	56	700	61	760	0.52	5.2	. . .	. . .	10	1.2	0.30	3.0	32	400	280	3.5	. . .	7.5
Sintered Alnico 5	48	600	48	605	1.04	10.4	1.205	12.05	29	3.60	0.785	7.85	37	465	240	3.0	18	4.0
Sintered Alnico 6	61	760	63	790	0.88	8.8	1.15	11.5	22	2.75	0.55	5.5	40	500	320	4.0	12	4.5
Sintered Alnico 8	125	1,550	134	1,675	0.76	7.6	0.94	9.4	36	4.5	0.46	4.6	80	1,000	640	8.0	5.0	2.1
Cunife	44	550	44	555	0.54	5.4	0.59	5.9	12	1.5	0.40	4.0	26	325	200	2.5	12	3.7
Bonded ferrite A	155	1,940	. . .	. . .	0.214	2.14	. . .	. . .	8	1.0	0.116	1.16	. . .	. . .	960	12.0	1.3	1.1
Bonded ferrite B	92	1,150	. . .	. . .	0.14	1.4	. . .	. . .	3	0.4	. . .	. . .	. . .	. . .	640	8.0	1.2	1.1
Sintered ferrite 1	145	1,800	276	3,450	0.22	2.2	. . .	. . .	8	1.0	0.11	1.1	72	900	800	10.0	1.2	1.2
Sintered ferrite 2	175	2,200	185	2,300	0.38	3.8	. . .	. . .	27	3.4	0.185	1.85	132	1,650	800	10.0	1.1	1.1
Sintered ferrite 3	240	3,000	292	3,650	0.32	3.2	. . .	. . .	20	2.5	0.16	1.6	130	1,600	800	10.0	1.1	1.1
Sintered ferrite 4	175	2,200	185	2,300	0.40	4.0	. . .	. . .	30	3.7	0.215	2.15	135	1,700	960	12.0	1.2	1.05
Sintered ferrite 5	250	3,150	287	3,590	0.355	3.55	. . .	. . .	24	3.0	0.173	1.73	138	1,730	1,200	15.0	1.0	1.05
NdFeB (sintered)	848	10,600	>1,350	>17,000	1.16	11.6	. . .	. . .	255	32	0.60	6.0	425	5,300	>2,000	>25.0	1.13	. . .
Bonded NdFeB	430	5,400	720	9,000	0.69	6.9	. . .	. . .	76	9.5	0.315	3.15	240	3,000	. . .	. . .	1.05	. . .

Hot-pressed NdFeB	560	7,000	1,280	16,000	0.80	8.0	. . .	. . .	110	13.7	0.38	3.8	295	3,700	. . .	. . .	1.05	. . .
Hot-formed NdFeB	880	11,000	1,200	15,000	1.20	12.0	. . .	. . .	274	34.2	0.59	5.9	465	5,800	. . .	. . .	1.05	. . .
Platinum cobalt	355	4,450	430	5,400	0.645	6.45	. . .	. . .	74	9.2	0.35	3.5	215	2,700	1,600	20.0	1.2	1.2
Cobalt rare earth 1	720	9,000	1,600	20,000	0.92	9.2	0.98	9.8	170	21	. . .	. . .	. . .	. . .	2,400	30.0	. . .	. . .
Cobalt rare earth 2	640	8,000	>2,000	>25,000	0.86	8.6	. . .	. . .	145	18	0.44	4.4	330	4,100	2,400	30.0	. . .	1.05
Cobalt rare earth 3	535	6,700	>1,200	>15,000	0.80	8.0	. . .	. . .	120	15	0.40	4.0	295	3,700	2,400	30.0	. . .	1.1
Cobalt rare earth 4	640	8,000	>640	>8,000	1.13	11.3	. . .	. . .	240	30	0.60	6.0	400	5,000	>1,600	>20.0	1.2	. . .

For nominal compositions, see Table 1; for mechanical and physical properties, see Table 3

Table 3 Nominal mechanical and physical properties of selected permanent magnet materials

Designation	Density, g/cm^3	Tensile strength		Transverse modulus of rupture		Hard hardness, HRC	Coefficient of linear expansion		Electrical resistivity, n$\Omega \cdot$ m	Maximum service temperature	
		MPa	**ksi**	**MPa**	**ksi**		**μm/m · K**	**μin./in. · °F**		**°C**	**°F**
$3\frac{1}{2}$ % Cr steel	7.77	. . .	. . .	. . .	. . .	60-65	12.6	7.01	290	. . .	. . .
6% W steel	8.12	. . .	. . .	. . .	. . .	60-65	14.5	8.06	300	. . .	. . .
17% Co steel	8.35	. . .	. . .	. . .	. . .	60-65	15.9	8.84	280	. . .	. . .
36% Co steel	8.18	. . .	. . .	. . .	. . .	60-65	17.2	9.56	270	. . .	. . .
Cast Alnico 1	6.9	28	4.1	96	14	45	12.6	7.01	750	540	1004
Cast Alnico 2[(a)]	7.1	21	3.1	52	7.5	45	12.4	6.89	650	540	1004
Cast Alnico 3	6.9	83	12	157	23	45	13.0	7.23	600	480	896
Cast Alnico 4	7.0	63	9.1	167	24	45	13.1	7.28	750	590	1094
Cast Alnico 5[(a)(b)]	7.3	37	5.4	73	11	50	11.4	6.34	470	540	1004
Cast Alnico 5DG	7.3	36	5.2	62	9.0	50	11.4	6.34	470	. . .	. . .
Cast Alnico 5-7	7.3	34	4.9	55	8.0	50	11.4	6.34	470	540	1004
Cast Alnico 6[(a)]	7.4	157	23	314	46	50	11.4	6.34	500	540	1004
Cast Alnico 7	7.3	108	16	. . .	. . .	60	11.4	6.34	580	. . .	. . .
Cast Alnico 8	7.3	64	9.3	. . .	. . .	56	11.0	6.12	500	540	1004
Cast Alnico 9	7.3	48	6.9	55	8.0	56	11.0	6.12	. . .	. . .	. . .
Cast Alnico 12	7.4	275	40	343	50	58	11.0	6.12	620	480	896
Sintered Alnico 2	6.8	451	65	480	70	43	12.4	6.89	680	480	896
Sintered Alnico 4	6.9	412	60	588	85	. . .	13.1	7.28	680	590	1094
Sintered Alnico 5	7.0	343	50	392	57	44	11.3	6.28	500	540	1004
Sintered Alnico 6	6.9	382	55	755	110	44	11.3	6.28	530	540	1004
Sintered Alnico 8	7.0	. . .	. . .	382	55	43	. . .	. . .	. . .	. . .	. . .
Bonded ferrite A[(c)]	3.7	4.4	0.63	. . .	. . .	. . .	94	52	~10^{13}	95	203
Sintered ferrite 1[(d)]	4.8	49	7.1	. . .	. . .	. . .	10	6	~10^{13}	400	752
Sintered ferrite 2	5.0	. . .	. . .	. . .	. . .	. . .	10	6	~10^{13}	400	752
Sintered ferrite 3	4.5	. . .	. . .	. . .	. . .	. . .	18	10	~10^{13}	400	752
Sintered ferrite 4	4.8	. . .	. . .	. . .	. . .	. . .	. . .	. . .	10^{13}	400	752
Sintered ferrite 5	4.5	. . .	. . .	. . .	. . .	. . .	. . .	. . .	10^{13}	. . .	. . .
Sintered NdFeB	7.5	830	120	. . .	. . .	58	5	3	1600	150	300
Bonded NdFeB	5.8	13.5	2	. . .	. . .	36	. . .	. . .	10^9	130	265
Hot-pressed NdFeB	7.5	. . .	. . .	. . .	. . .	58	. . .	. . .	1600	150	300
Hot-formed NdFeB	7.4	. . .	. . .	. . .	. . .	58	. . .	. . .	1600	150	300
Cunife	8.6	686	99	. . .	. . .	95 HRB	12	6.7	180	350	662
Platinum cobalt	15.5	1370	199	1,570	230	26	11	6.1	280	350	662
Cobalt rare earth[(e)]	8.2	3430	498	13,730	1,990	50	511; 131	284; 72.8	500	250	482

See Table 1 for composition, Curie temperatures and magnetic orientations; see Table 2 for nominal magnetic properties.

(a) Specific heat: 460 J/kg · K (0.11 Btu/lb · °F).

(b) Thermal conductivity: 25 W/m · K (170 Btu · in./ft^2 · h · °F) at room temperature.

(c) Thermal conductivity: 0.62 W/m · K (4.3 Btu · in./ft^2 · h · °F).

(d) Thermal conductivity: 5.5 W/m · K (38 Btu · in./ft^2 · h · °F).

(e) Specific heat: 380 J/kg · K (0.09 Btu/lb · °F). Thermal conductivity: 15 W/m · K (104 Btu · in./ft^2 · h · °F)

Selection and Application. Over the years, the number and range of applications utilizing permanent magnets has increased dramatically. Some of the more predominant applications include aircraft magnetos, alternators, magnetos for lawn mowers, garden tractors, and outboard motors; small and large direct current (dc) motors (including automotive motors); acoustic transducers; magnetic couplings; magnetic resonance imaging; magnetic focusing systems; ammeters and voltmeters; and watt-hour meters. Table 4 lists the materials recommended for various applications.

Table 4 Applications of permanent magnet materials

Application	Recommended material	Primary reason for selection	Alternative material	Condition or reason favoring selection of alternative material
Aircraft magnetos, military or civilian	SmCo	Maximum energy per unit volume	Cast Alnico 5	Availability or cost restraint
Alternators	SmCo	Compactness and reliability	Ferrite Alnico	Where space is available for a larger volume of material of lower magnetic energy and cost
Magnetos for lawn mowers, garden tractors, and outboard engines	Ferrite	Adequate magnetic energy at lower cost than Alnico	Alnico NdFeB	Higher energy material is required
Small direct current motors	Bonded ferrite	Shape favors fabrication; adequate magnetic energy at lower cost	Bonded NdFeB Sintered ferrite	Higher magnetic energy is required
Large direct current motors	SmCo	Maximum energy per unit volume	NdFeB	Where lower cost is required, operating temperature is low
Automotive direct current motors	Ferrite	Adequate magnetic energy at lower cost than alternate materials	Bonded NdFeB	Higher magnetic energy and less weight
Automotive cranking motors	Ferrite	Adequate magnetic energy at lower cost than alternate materials	Bonded NdFeB	Higher magnetic energy and less weight
Voice coil motors (computers)	NdFeB	High energy	SmCo	Availability
Acoustic transducers	Ferrite	Low cost	NdFeB	Higher magnetic energy allows smaller size and weight
Magnetic couplings (small gap)	Ferrite	Adequate magnetic energy at lower cost	Bonded NdFeB	Higher torque is required
Magnetic couplings (large gap)	NdFeB	High energy	SmCo	High operating temperature
Transport systems	NdFeB	High Energy	SmCo	Availability
Separators	Ferrite	Adequate magnetic energy at lower cost	NdFeB	High magnetic energy required
Magnetic resonance imaging	NdFeB	High energy	Ferrite	Where space is available for a larger volume of material of lower energy
Magnetic focusing systems	NdFeB	High energy	SmCo	High operating temperatures or low-temperature coefficient is required
Synchronous hysteresis motors	Isotropic FeCrCo	Shape favors fabrication from wrought material	Cobalt steel	Availability
Holding devices	Ferrite	Adequate magnetic energy at low cost	Alnico	Where holding force versus temperature must not vary over wide ranges
Ammeters and voltmeters	Alnico	Low temperature coefficient	Not available	. . .
Watt-hour meters	Alnico 5 or 6	Low temperature coefficient	Not available	. . .

Optimum Alloy Usage

Stabilization and Stability

There is an important group of permanent magnet applications where the accuracy or performance of the device is drastically affected by very small changes (1% or less) in the strength of the magnet. These applications include braking magnets for watt-hour meters, magnetron magnets, special torque motor magnets, and most dc panel and switchboard instrument magnets. Operation of these devices requires extreme accuracy over a moderate range of conditions or moderate accuracy over an extreme range of conditions.

If the nature and magnitude of the conditions are known, it often is possible to predict the flux change. It also may be possible, by exposing the magnet to certain influences in advance, to render the magnet insensitive to subsequent changes in service. For many years, permanent magnets in instruments have exhibited long-term stability of the order of one part per thousand (0.1%). More recently, investigations in conjunction with inertial guidance systems for space vehicles have shown that long-term stability of the order of one to 10 ppm (0.0001 to 0.001%) can be achieved. This incredible stability of a magnetic field achieved with modern permanent magnets contrasts sharply with the instability of very early (steel) permanent magnets, in which both structural and magnetic changes caused a significant loss of magnetization with time.

Irreversible Changes

Losses in magnetization with time can be classified as reversible or irreversible. Irreversible changes are defined as changes where the affected properties remain altered after the influence responsible for the change has been removed. For example, if a magnet loses field strength under the influence of elevated temperature and if the flux does not return to its original value when the magnet is cooled to room temperature, the change is considered irreversible.

Temperature Effects. The properties of a magnet vary with temperature in a manner that usually can be predicted. The variation of B_{is}, with temperature can be calculated from theory, provided detailed knowledge of the crystallographic and magnetic structure of the magnetic phase is available. In many other instances, such information is not yet available, but direct measurements of B_{is} versus T have been made. Both irreversible and reversible magnetization losses have been documented.

Changes in H_{ci} with temperature can be predicted from the changes with temperature of anisotropy and magnetization. This assumes knowledge of the physical origin of all anisotropies contributing to H_{ci}. For a case where shape anisotropy is dominant, calculated and experimental results also are in good agreement, especially when the small crystal anisotropy contributions are considered. In the case of Alnico, crystal anisotropy is more in evidence. In addition, there is greater uncertainty as to the effect of the so-called nonmagnetic phase, especially at lower temperatures where the nonmagnetic phase can contribute appreciable magnetization. In the case of steels, the temperature dependence based on the inclusion mechanism is difficult to predict. Demagnetization curves can change in both shape and peak with changes in temperature.

Changes in Metallurgical State. Irreversible changes begin to occur at different temperatures for different alloys. These changes usually depend on both time and temperature, and thus short exposures above the recommended temperatures may be tolerated. These changes can take the form of growth of the precipitate phase, such as in Alnico and Cunife; precipitation of another phase, such as γprecipitation in Alnico; an increase in the amount of an ordered phase, such as in platinum-cobalt; an increase in grain size, as in $SrO{\cdot}6Fe_2O_3$; oxidation, as occurs with metals, or reduction, as occurs with oxides, radiation damage, cracking, or changes in dimensions.

Irreversible metallurgical changes often can be counteracted, and original properties restored, by a suitably chosen thermal treatment. For example, if Alnico 5 has become degraded by exposure to 700 °C (1290 °F), it can be solution treated at 1300 °C (2370 °F), cooled in a magnetic field, and aged at 600 °C (1110 °F) to reattain the optimum metallurgical structure.

A nuclear environment is known to cause changes in metallurgical structure and thus changes in metallurgical structure and thus can cause changes in magnetic properties. Permanent magnet materials tested were not affected by neutron (n) irradiation at levels below approximately 3×10^{17} n/cm^2 (2×10^{18} n/in.^{2}). Results of later work at levels up to 10^{20} n/cm^2 (6×10^{20} n/in.^{2}) showed some degradation. The Alnico materials are not affected by radiation up to 5×10^{20} n/cm^2 (3×10^{21} n/in.^{2}) at neutron energies greater than 0.4 eV, and up to 2×10^{19} n/cm^2 (1×10^{20} n/in.^{2}) for neutron energies greater than 2.9 MeV. Radiation effects were found to be independent of temperature, but high temperatures tended to counteract radiation effects. More recently developed permanent magnet materials such as Sm_2Co_5 and NdFeB are more sensitive to radiation.

Changes in magnetic state can be caused by temperature effects, such as ambient temperature changes or statistical local temperature fluctuations within the material; mechanical effects, such as mechanical shock or acoustical noise; or magnetic field effects, such as external fields, circuit reluctance changes, or magnetic surface contacts. In all of these situations, the loss of magnetization can be restored by remagnetizing.

Mechanical shock and vibration add energy to a permanent magnet and decrease the magnetization in the same manner as discussed for the case of thermal energy. The only difference is that energy imparted thermally to the magnet is precisely kT, where k is the Boltzmann constant and T is the temperature, whereas the energy imparted mechanically usually is not known. Thus, repetitive shocks or continual vibration should decrease the magnetization by the same logarithmic relations as for thermal effects, but where time is replaced, for example, by number of impacts.

Little work has been done regarding stabilization to minimize mechanical effects because it is seldom found necessary. It is generally conceded that modern permanent magnet materials are not affected by mechanical shock.

Reversible Changes

A loss of magnetization caused by a disturbing influence, such as temperature or an external magnetic field, is considered reversible if the original properties of the magnet return when the disturbing influence is removed.

Time Effects at Constant Temperature. In ferromagnetic materials, the intensity of magnetization does not instantly attain its equilibrium value when the applied field is suddenly changed. This time dependence can be due to eddy current effects or to reversible or irreversible magnetic viscosity. In general, eddy current effects are important only for a very short time--normally, less than a second after a change in the applied field. Such effects are not considered here. Reversible magnetic viscosity has been shown to be due to ionic diffusion in the crystal lattice and thus has a time-temperature dependence characteristic of diffusion processes. The time constant is:

$$\tau = \tau_\infty \exp\,(E/RT) \qquad \textbf{(Eq 3)}$$

where τ_∞ is the time constant at infinite temperature, R is the reluctance (the reciprocal of permeance), and E is the activation energy, normally 0.1 to 1 eV. The time constant appears to be important only in magnetically soft materials, and only at high frequencies.

Irreversible magnetic viscosity is important to the stability of permanent magnets. Irreversible magnetic viscosity is due to the influence of thermal fluctuations on magnetization or the domain process responsible for magnetization. The effect of thermal agitation has been considered in terms of the energy required to activate irreversible domain processes. The time-temperature dependence of magnetization was shown to be given by:

$$M(t) = S \ln t \qquad \textbf{(Eq 4)}$$

where $S = \lambda N M_s kT$. Here, N is the number of blocks, or regions of magnetization M_s per unit volume, and λ is the constant probability density of energy E of all these blocks. Because these factors are all relatively independent of temperature (except near the Curie temperature), S is nearly directly proportional to T. The results of experiments are in agreement with this equation. Aging at room temperature results in losses in magnetization for many materials.

Design Considerations

Stability can have a significant influence on choice of magnet material, as well as on component shape and magnetic circuit arrangement. For example, the rather drastic change in coercive force of oriented hard ferrite with temperature requires special considerations in design. Here, the lowest permeance coefficient (B/H) that can be used is established by stability considerations rather than by magnetic circuit analysis.

For the more widely used permanent magnet materials, reversible changes in magnetization are encountered by cooling below room temperature. Because the reversible remanence changes are closely approximated by a straight line, a reversible temperature coefficient is listed in magnetic property tabulations. The values of the temperature coefficient vary with the material. When the values of the coefficient are very small, they can be of a different sign for different magnet shapes. Consequently, it is often possible to carefully design magnet shape to yield very small variations in remanence with temperature. Similar changes may result on heating above room temperature. It is important to distinguish between irreversible losses and reversible changes. It is common practice prior to use to cycle a magnet between the temperature extremes to be encountered in service. Nearly all of the irreversible loss is encountered in one temperature cycle, but in some instances four or five cycles may be necessary.

In applications that are extremely sensitive to magnetization changes, it is very common to use a temperature compensating circuit to counteract reversible changes over the operating temperature range. Temperature-sensitive iron-nickel alloys are used as magnetic shunts for this purpose. A shunt is mounted beside the permanent magnet and simply diverts flux from the air gap as the temperature decreases. Temperature compensation by shunting requires overdesign of the magnet to allow for the loss in flux through the shunt at low operating temperatures.

Exposure at Very High Temperatures. There is considerable interest in using permanent magnets at temperatures approaching the Curie temperature of the permanent magnet material. The anisotropic Alnico 5 and Alnico 6 have been considered for use at 500 to 700 °C (930 to 1290 °F). At these temperatures, metallurgical effects as well as irreversible and reversible temperature effects are present. Alnico 5 exposed to 700 °C (1290 °F) for 20 h resulted in the reduction of $(BH)_{\max}$ and H_c to approximately one half of their initial values. It is possible to program such changes into equipment and devices to allow permanent magnets to function for a limited time at extreme temperatures.

Stress Effects. Some magnets subjected to tension of compression show large changes in properties. This is especially true of Vicalloy and Cunife. The changes are reversible, often even after considerable deformation has occurred. The changes are due to the contribution that stress makes to the total anisotropy of the system.

Magnetization Prior to Use. Magnets are magnetized in applied fields supplied by dc or pulsed-current electromagnets. Where practical, saturating magnetizing fields are recommended to gain full use of magnetic potential energy. Most magnets are demagnetized by heating to the Curie temperature or by applying an ac or dc field to reduce the measured induction to zero. Materials such as Alnico and samarium cobalt cannot be demagnetized by exposure to their Curie temperature because the metallurgical changes alter the permanent magnet properties.

Selected References

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Superconducting Materials

Introduction

SUPERCONDUCTORS are materials that exhibit a complete disappearance of electrical resistivity on lowering the temperature below a critical temperature (T_c). For all superconductors presently known, the critical temperatures are well below room temperature, and they are attained by cooling with liquified gas (helium or nitrogen), either at or below atmospheric pressure. A superconducting material must also exhibit perfect diamagnetism, that is, the complete exclusion of an applied magnetic field from the bulk of the superconductor. Superconductivity permits electric power generators and transmission lines to have capacities many times greater than recently possible. It also allows the development of levitated transit systems capable of high speeds and provides an economically feasible way of producing the large magnetic fields required for the confinement of ionized gases in controlled thermonuclear fusion.

Basic Principles

The critical temperature varies from superconductor to superconductor, but lies between approximately 1 and 20 K for metals and alloys. More recently developed ceramic superconductors have critical temperatures exceeding 100 K. At temperatures below T_c, the superconducting state will cease upon application of a sufficiently large magnetic field, termed the critical field, H_c, which depends on temperature and decreases with increasing temperature. The same is true for current density; that is, a critical applied current density, J_c, exists below which a material is superconductive. Figure 1 shows how these three factors are interrelated. Materials lying within the $T_cH_cJ_c$ envelope boundary in Fig. 1 will be superconductive; outside the boundary, conduction is normal.

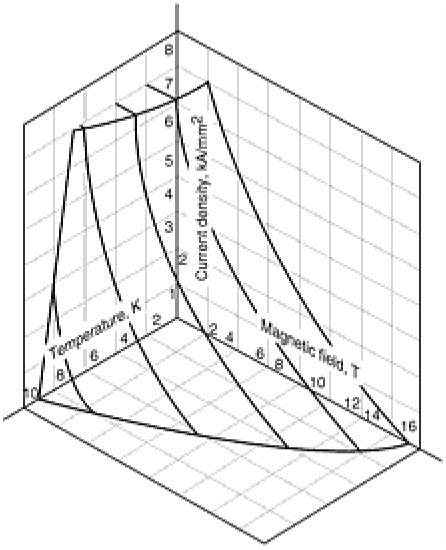

Fig. 1 Critical temperature, current density, and magnetic field boundary separating superconducting and normal conducting states. These data, which are for a niobium-titanium superconducting alloy, are based on measurements at 4.2 K.

On the basis of magnetic response, superconducting materials can be divided into two classifications designated as type I and type II. Type I materials, while in the superconducting state, are completely diamagnetic; that is, all of an applied magnetic field will be excluded from the body of the material. This phenomenon, known as the Meissner effect, is shown schematically is Fig. 2. As H is increased, the material remains diamagnetic until the critical magnetic field H_c is reached. At this point, conduction becomes normal, and complete magnetic flux penetration occurs. Several metallic elements including aluminum, lead, tin, and mercury belong to the type I group.

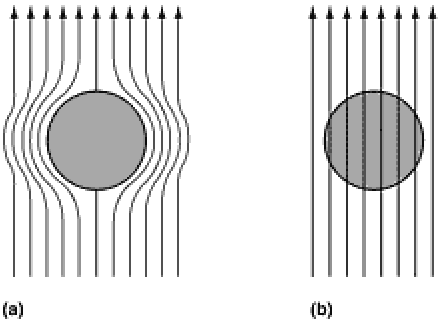

Fig. 2 Schematic of the Meissner effect. (a) While in the superconducting state, a body of material (shaded circle) excludes a magnetic field (arrows) from its interior. (b) The magnetic field penetrates the same body of material once it becomes normally conductive.

Type II superconductors are completely diamagnetic at low applied fields, and field exclusion is total. However, the transition from the superconducting state to the normal state is gradual and occurs between lower critical and upper critical fields, designated H_{c1} and H_{c2}, respectively. The magnetic flux lines begin to penetrate into the body of material at H_{c1}, and with increasing applied magnetic field, this penetration continues; at H_{c2}, field penetration is complete. For fields between H_{c1} and H_{c2}, the materials exists in what is termed a "mixed state"--superconductivity persists in the mixed state up to H_{c2}, above which the material is a normal conductor. Type II superconductors are preferred over type I for most practical applications by virtue of their higher critical temperatures and critical magnetic fields. Table 1 compares the properties of various type I and type II superconducting materials.

Table 1 Approximate superconducting properties of selected superconducting materials

Material	Type	Critical temperature, T_c at 0 T	Parameters at 4.2 K			
			Thermodynamic critical field, T, at			**Critical current density (J_c),kA/mm^2**
			$\mu_0 H_c$	$\mu_0 H_{c1}$	$\mu_0 H_{c2}$	
Pb	I	7.3	0.0803(a)	. . .	. . .	. . .
Nb	II	9.3	0.37	0.25	0.41	. . .
Nb45-50-Ti	II	8.9-9.3	0.16	0.009	10.5-11.0	3 (at 5 T)
Nb_3Sn	II	18	0.46	0.034	19-25	10 (at 5 T)
Nb_3Ge	II	23	0.16	0.004	36-41	10 (at 5 T)
NbN	II	16-18	0.16	0.004	20-35	10 (at 5 T)
$PbMo_6S_8$	II	14-15	0.4	0.005	40-55	0.8 (at 5 T)
$YBa_2Cu_3O_7$	II	92	0.5	0.05(b)	60(b)	1 (at 77 K, 0 T)(d)

(a) Thermodynamic critical field at 0 K.

(b) Measured with field parallel to the *c* axis.

(c) Measured with field parallel to the *a*-*b* plane.

(d) Epitaxial thin film, current in the *a*-*b* plane

Superconductor Categories

Superconductivity is observed in several hundred materials. These include more than half of the metallic elements and a wide range of alloys and compounds (type II superconductors). To date, however, the materials that have received the most attention are niobium-titanium superconductors (the most widely used superconductor), A15 compounds (in which class the important ordered intermetallic Nb_3Sn lies), ternary molybdenum chalcogenides (Chevrel phases), and high T_c ceramic superconductors. Figure 3 compares the critical temperatures for metallic and ceramic superconducting materials. The advantage of the higher T_c ceramics is that they can be cooled with liquid nitrogen, which is much cheaper and more abundant than helium (the cooling medium for metallic superconductors). The brittle nature of ceramic superconductors, however, limits the ability of these materials to be fabricated into useful forms such as wires. The goal of superconductor research is to develop fabricable conductors that can be cooled with conventional refrigeration equipment or function at room temperature.

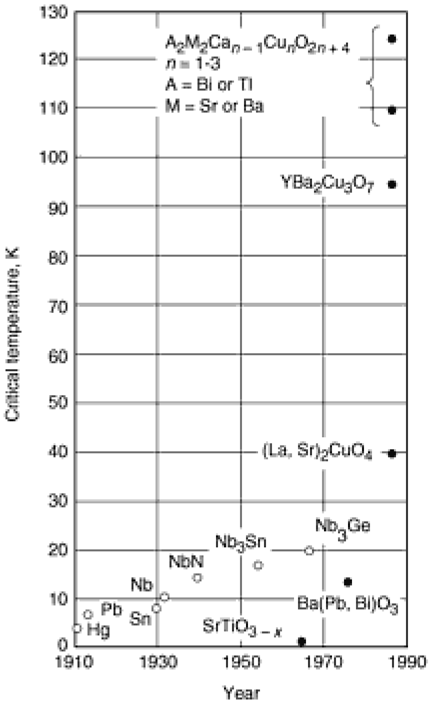

Fig. 3 The critical temperature for various superconducting materials as a function of their date of development. The open circles are metallic superconductors, while the closed circles are ceramic.

Niobium-titanium superconductors are actually composite wires that consist of niobium-titanium filaments (<10 μm in diameter) embedded in a ductile matrix (stabilizer) that must provide high electrical conductivity and thermal conductivity, high heat capacity, and good mechanical strength at cryogenic temperature. High-purity, oxygen-free copper (C10100) satisfies all of these requirements and is the most frequently stabilizing matrix material. Commercially pure aluminum (alloy 1100, 99.0% Al) and copper-nickel alloy (typically in concentrations of 90 to 10 or 70 to 30) matrices have also been utilized. The filament alloy most widely used is Nb-46.5Ti. Binary niobium-titanium superconductors in the range of 45 to 50% Ti exhibit T_c values of 9.0 to 9.3 K. Composite conductors containing as few as one to as many as 25,000 filaments have been processed by advanced extrusion and wire-drawing techniques. Important applications for niobium-titanium superconductors include magnets for use in magnetic resonance imaging (MRI) devices used in hospitals, high-energy physics pulsed accelerator magnet applications (particle accelerators), and devices for magnetically confining high-energy plasma for thermonuclear fusion.

A15 superconductors (A15 refers to a cubic crystal type in the Strukturbericht system) are brittle intermetallic compounds with the chemical formula A_3B, where A is a transition metal and B can be either a transition metal or nontransition element. Of the 76 known A15 compounds, 46 are known to be superconducting. Important examples include Nb_3Ge (T_c = 23 K), Nb_3Ga (T_c = 20.3 K), Nb_3Al (T_c = 18.9 K), Nb_3Sn (T_c = 18.3 K), V_3Si (T_c = 17.1 K), and V_3Ga (T_c = 15.4 K). Because of ease of fabrication, Nb_3Sn is the most commercially important A15 compound. Like niobium-titanium superconductors, Nb_3Sn is also assembled into multifilamentary wires embedded by various techniques into a copper stabilizing matrix (Fig. 4). Diffusion barriers (niobium, tantalum, or vanadium) are also used to prevent reaction between the matrix and filaments during elevated-temperature processing. Applications for Nb_3Sn-based superconductors include large commercial solenoid magnets, alternating current (ac) motors, and generators for power generation, power transmission cables, and high-energy physics and fusion technology applications.

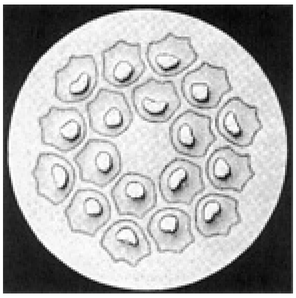

Fig. 4 Cross section of a multifilamentary Nb_3Sn superconductor wire (20 mm, or 0.78 in. diam). The 18 filaments in the wire each have individual bimetal diffusion barriers composed of concentric rings of niobium around vanadium. The matrix surrounding the filaments is copper. 75×

The ternary molybdenum chalcogenides represent a vast class of materials with a general formula of $M_xMo_6X_8$, where M is a cation and X is a chalcogen (sulfur, selenium, or tellurium). Most of the research on these materials has centered around $PbMo_6S_8$ (PMS) and $SnMo_6S_8$ (SMS), the former having a T_c of 14 to 15 K. The PMS or SMS wire is embedded in a copper or molybdenum matrix. A niobium diffusion layer is used in the case of copper matrices.

High-temperature superconductors (T_c values exceeding 90 K) are ceramic oxides in wire, tape, or thin-film form. The systems that have been extensively studied include Y-Ba-Cu-O (most notably $YBa_2Cu_3O_7$ with a T_c = 92 K), Bi-Sr-Ca-Cu-O (T_c = 110 K), and Tl-Ba-Ca-Cu-O (T_c > 120 K). Oxide-base superconductors in wire or tape form are produced by packing the powder in a silver tube, which is then swaged or drawn into a wire, or if desired, rolled into a tape.

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Electrical Resistance Alloys

Introduction

ELECTRICAL RESISTANCE ALLOYS include both the types used in instruments and control equipment to measure and regulate electrical characteristics and those used in furnaces and appliances to generate heat. In the former applications, properties near ambient temperature are of primary interest: in the latter, elevated-temperature characteristics are of prime importance. In common commercial terminology, electrical resistance alloys used for control or regulation of electrical properties are called resistance alloys, and those used for generation of heat are referred to as heating alloys. Electrical resistance materials of a third class, used in applications where heat generated in a metal resistor is converted to mechanical energy, are termed thermostat metals.

Resistance Alloys

The primary requirements for resistance alloys are uniform resistivity, stable resistance (no time-dependent aging effects), reproducible temperature coefficient of resistance, and low thermoelectric potential versus copper. Properties of secondary importance are coefficient of expansion, mechanical strength, ductility, corrosion resistance, and ability to be joined to other metals by soldering, brazing or welding. Availability and cost are also factors.

Table 1 lists nominal compositions and physical properties of metals and alloys used to make resistors for instruments and controls.

Table 1 Typical properties of electrical resistance alloys

Basic composition, %	Resistivity(a), nΩ · m(b)	TCR, ppm/°C(c)	Thermoelectric potential versus Cu, μV/°C	Coefficient of thermal expansion(d), μm/m · °C	Tensile strength(a)		Density(a)	
					MPa	**ksi**	**g/cm^3**	**lb/in.^{3}**
Radio alloys								
98Cu-2Ni	50	1400 (25-105 °C)	-13 (25-105 °C)	16.5	205-410	30-60	8.9	0.32
94Cu-6Ni	100	700 (25-105 °C)	-13 (25-105 °C)	16.3	240-585	35-85	8.9	0.32
89Cu-11Ni	150	450 (25-105 °C)	-25 (25-105 °C)	16.1	240-515	35-75	8.9	0.32
78Cu-22Ni	300	180 (25-105 °C)	-36 (0-75 °C)	15.9	345-690	50-100	8.9	0.32
Manganins								
87Cu-13Mn	480	±15 (15-35 °C)	-1 (0-50 °C)	18.7	275-620	40-90	8.2	0.30
83Cu-13Mn-4Ni	480	±15 (15-35 °C)	-1 (0-50 °C)	18.7	275-620	40-90	8.4	0.31
85Cu-10Mn-4Ni(e)	380	±10 (40-60 °C)	-1.5 (0-50 °C)	18.7	345-690	50-100	8.4	0.31
Constantans								
57Cu-43Ni	500	±20 (25-105 °C)	-43 (25-105 °C)	14.9	410-930	60-135	8.9	0.32
55Cu-45Ni	500	±40 (-55-105 °C)	-42 (0-75 °C)	14.9	455-860	66-125	8.9	0.32
53Cu-44Ni-3Mn	525	±70 (-55-105 °C)	-38 (0-100 °C)	14.9	410-930	60-135	8.9	0.32
Ni-Cr-Al								
75Ni-20Cr-3Al-2(Cu, Fe, or Mn)	1333	±20 (-55-105 °C)	1.0 (25-105 °C)	12.6	825-1380	120-200	8.1	0.29
72Ni-20Cr-3Al-5Mn	1375	±20 (-55-105 °C)	1.0 (25-105 °C)	13	690-1380	100-200	7.1	0.26
Nickel-base alloys								
78.5Ni-20Cr-1.5Si	1080	80 (25-105 °C)	3.9 (25-105 °C)	13.5	790-1380	115-200	8.3	0.30
76Ni-17Cr-4Si-3Mn	1330	±20 (-55-105 °C)	-1 (20-100 °C)	15	900-1380	130-200	7.8	0.28
71Ni-29Fe	208	4300 (25-105 °C)	-40 (25-105 °C)	15	480-1035	70-150	8.4	0.31
68.5Ni-30Cr-1.5Si	1187	90 (25-105 °C)	-1.2 (25-105 °C)	12.2	825-1380	120-200	8.1	0.29
60Ni-16Cr-22.5Fe-1.5Si	1125	150 (25-105 °C)	0.9 (25-105 °C)	13.5	725-1345	105-195	8.4	0.30
37Ni-21Cr-40Fe-2Si	1080	300 (20-100 °C)	. . .	16.0	585-1135	85-165	7.96	0.288
35-Ni-20Cr-43.5Fe-1.5Si	1000	400 (25-105 °C)	-1.1 (25-105 °C)	15.6	585-1135	85-165	8.1	0.29
Fe-Cr-Al								
73.5Fe-22Cr-4.5Al	1350	60 (25-105 °C)	-3.0 (0-100 °C)	11	690-965	100-140	7.25	0.262
73Fe-22Cr-5Al	1390	40 (25-105 °C)	-2.8 (0-100 °C)	11	690-965	100-140	7.15	0.258
72.5Fe-22Cr-5.5Al	1450	20 (25-105	-2.6 (0-100 °C)	11	690-965	100-	7.1	0.256

		°C)				140		
81Fe-15Cr-4Al	1250	±50 (25-105 °C)	-1.2 (0-100 °C)	11	620-900	90-130	7.43	0.268
Pure metals								
Aluminum (99.99+)	26.55	4290[(a)]	-3.4 (0-50 °C)	23.9[(a)]	50-110	7-16	2.70	0.098
Copper (99.99)	16.73	4270 (0-50 °C)	0	16.5[(a)]	115-130	17-19	8.96	0.324
Gold (99.999+)	23.50	4000 (0-100 °C)	0.2 (0-100 °C)	14.2[(a)]	130	19	19.32	0.698
Iron (99.94)	970	5000[(a)]	12.2 (0-100 °C)	11.7[(a)]	180-220	26-32	7.87	0.284
Molybdenum (99.9)	52	3300[(a)]	6.9 (0-100 °C)	4.9	690-2140	100-310	10.22	0.369
Nickel (99.8)	80	6000 (20-35 °C)	-22 (0-75 °C)	15	345-760	50-110	8.90	0.322
Platinum (99.99+)	105	3920 (0-100 °C)	7.6 (0-100 °C)	8.9[(a)]	125	18	21.45	0.775
Silver (99.99)	16	4100[(a)]	-0.2 (0-100 °C)	19.7	125	18	10.49	0.379
Tantalum (99.96)	125	3820 (0-100 °C)	-4.3 (0-100 °C)	6.5[(a)]	690-1240	100-180	16.6	0.600
Tungsten (99.9)	55	4500[(a)]	3.6 (0-100 °C)	4.3[(a)]	1825-4050	265-590	19.25	0.695

(a) At 20 °C (68 °F).

(b) To convert to Ω·circular-mil/ft, multiply by 0.6015.

(c) Temperature coefficient of resistance is $(R - R_0)/R_0\ (t - t_0)$, where R is resistance at t °C and R_0 is resistance at the reference temperature t_0 °C.

(d) At 25 to 105 °C.

(e) Shunt manganin

Resistance alloys must be ductile enough so that they can be drawn into wire as fine as 0.01 mm (0.0004 in.) in diameter or rolled into narrow ribbon from 0.4 to 50 mm ($\frac{1}{64}$ to 2 in.) wide and from 0.025 to 3.8 mm (0.001 to 0.15 in.) thick.

Alloys must be strong enough to withstand fabrication operations, and it must be easy to procure an alloy that has consistently reproducible properties. For instance, successive batches of wire must have closely similar electrical characteristics: if properties vary from lot to lot, resistors made of wire from different batches may cause a given model of instrument to exhibit widely varying performance under identically reproduced conditions or may cause large errors in a given instrument when a resistor from one batch is used as a replacement part for a resistor from another batch.

Coefficients of expansion of both the resistor and the insulator on which it is wound must be considered because stresses can be established that will cause changes in both resistance and temperature coefficient of resistance. It is equally important that consideration be given to the choice between single-layer and multiple-layer wound resistors because of the difference in rate of heat dissipation between the two styles.

In design of primary electrical standards of very high accuracy, cost of resistance material is not a consideration. For ordinary production components, however, cost may be the deciding factor in material selection.

Resistors

Resistors for electrical and electronic devices can be divided into two arbitrary classifications on the basis of permissible error: those employed in precision instruments in which over-all error is considerably less than 1% and those employed where less precision is needed. The choice of alloy for a specific resistor application depends on the variation in properties that can be tolerated.

In many electronic devices, resistors with error in resistance value of 5 to 10% are entirely satisfactory. Most resistors for this classification are made of carbon. Carbon resistors are not discussed in this article. This section is concerned chiefly with metallic resistors such as wirewound precision resistors and potentiometers, resistance thermometers, and ballast resistors.

Some applications of resistance materials require devices with large thermal coefficients of resistance, either positive or negative. A device of this type is called a thermistor. Thermistors are made almost exclusively of ceramic semiconductor materials.

Precision resistors (those with less than 1% error) require careful material selection. The ideal material for a precision resistor should have a thermal coefficient of resistance equal to zero for the temperature range over which the resistor will operate. In addition, to ensure freedom from thermoelectric effects, it should have a small or negligible thermoelectric potential versus copper, which is the material normally used for the connecting conductor. Temperature differentials may exist among various junctions between a resistance wire and a connecting wire, resulting in a network of thermocouples that can cause parasitic electromotive forces in the circuits; this effect is especially critical in precise direct current (dc) circuits. In an apparatus where extreme precision is required, it is advisable to make the connecting wires of the same material as the resistors or to design the apparatus so that all dissimilar metal junctions are at the same operating temperature.

Selection of a material for, and specific dimensions of, a precision resistor must include consideration of equipment size and heat-dissipation characteristics. Temperature excursions from the ambient or from a specified operating temperature may be undesirable, because they can cause net changes in resistance that will affect the stability or accuracy of the instrument. The magnitude of the change in resistance can be calculated using the temperature coefficient of resistance. For example, a resistor made of a low resistivity material could be several times larger than one made of a higher-resistivity material and yet achieve the same total resistance. The large resistor would have a much greater surface area, could dissipate much more heat, and thus, despite its low resistivity, attain a lower steady-state temperature than would be possible for a small, high-resistivity resistor operating under the same conditions. Alloys used for precision resistors generally have resistivities ranging from 500 to 1350 nΩ · m (300 to 800 Ω· circular-mil/ft).

Resistance thermometers are commonly made of copper, nickel, or platinum; these devices are precision resistors whose resistance change with temperature is stable and reproducible over specified ranges of temperature. For resistance thermometers, the larger the temperature coefficient of the material, the greater the accuracy and ease of measurement. Temperature coefficients of relatively pure metals are greatly affected by small amounts of impurities. In fact, one of the most sensitive tests of the purity of a metal is measurement of its temperature coefficient of resistivity, which decreases sharply with increasing impurity or alloy content.

Ballast resistors are used extensively in industrial circuits to maintain constant currents over long periods of time. In such an application, a ballast resistor must be able to dissipate energy in such a way as to control current over a wide range of voltages. Wires with the proper temperature coefficient of resistance can be made to change resistance rapidly with changes in current, due to self heating, in such a manner that the current in the circuit will remain nearly constant even when there are fluctuations in voltage across the circuit. Because ballast resistors operate at elevated temperatures, mechanical properties are important also. Typical materials used in ballast resistors are pure iron, pure nickel, and nickel-iron alloys such as 71Ni-29Fe (see Table 1).

Reference resistors and virtually all other applications of resistance alloys demand temperature coefficients of resistance lower than ±20 ppm/°C (±20 $\mu\Omega/\Omega$ · °C). This requirement stems from the fact that, for these applications, resistance errors resulting from the small changes in ambient temperature that are continually occurring cannot be tolerated. In the most demanding of these applications, resistors often are mounted in thermally insulated containers and are carefully maintained at a temperature slightly above the maximum anticipated ambient temperature.

The most important requirement of a resistor used as a reference standard is that its value be predictable within narrow limits over long periods of time. Many reference resistors exhibit a nearly linear change in resistance with time. Hence, resistance between dates of calibration can be determined by interpolation; resistance at future points in time can be determined by extrapolation, but undue reliance should not be placed on extrapolated values, Figure 1 shows the change in resistance with time for a 10 kΩ resistor made of a Ni-Cr-Al-Cu alloy.

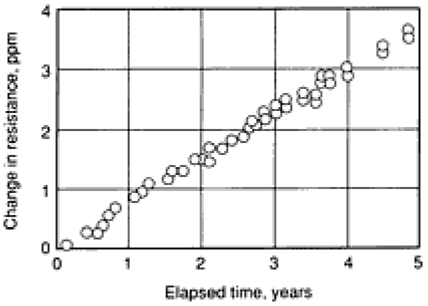

Fig. 1 Change in resistance of a 10 kΩ resistor with time

Stability, or the ability to maintain a specific value of resistance within narrow limits over a long period of time, is an important requirement of materials for precision resistors and reference resistors. Principal sources of instability are (a) relief of residual stresses during service; (b) time-dependent or time-temperature-dependent metallurgical changes, such as precipitation of a second phase; and (c) corrosion or oxidation; and (d) humidity.

Residual stresses often are relieved at room temperature over long periods of time through a process known as stress relaxation. Stress relaxation alters the resistance of a coil at a rate of change that increases with the original level of residual stress. For this reason, only carefully preannealed wires are used for precision resistors. Stresses induced during winding, weaving, or other operations in fabrication of resistors from preannealed wire must be kept to a minimum. Thorough annealing of finished resistors is not always possible because the wires can be enameled or coated with a textile insulation of only moderate resistance to heat. Either type of coating limits the temperature that can be used for stress relieving finished resistors to approximately 140 °C (285 °F).

Figure 2 shows the effect of residual stress on the stability of a manganin alloy subjected to different amounts of cold work. The top curve illustrates that a low-temperature, stress-relieving treatment substantially eliminates the stresses that would, in time, have been eliminated due to natural relaxation at room temperature.

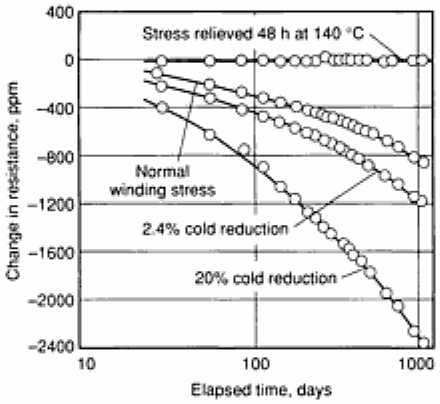

Fig. 2 Change in resistance of manganin resistors upon aging at room temperature

Resistors represented by the top curve were stress relieved at 140 °C (285 °F) for 48 h to stabilize their resistance within approximately 20 ppm of the nominal value. Resistors not stress relieved, as represented by the other curves, continue to change in resistance almost indefinitely. For most modern, hermetically sealed precision resistors annealed at 140 °C (285 °F), the change in resistance does not exceed 10 ppm/year, and for many it does not exceed 5 ppm/year. However, resistors made of manganin that are used as reference standards require greater stability, and stress relief at 140 °C (285 °F) is not adequate. One-ohm resistors of the best grade (the double-wall type) are treated as follows. A coil of wire is wound on a steel mandrel and annealed at approximately 500 °C (930 °F) in a protective atmosphere for 6 h or more. The coil is removed and slipped over an insulated tube of the same diameter as the mandrel, and then is hermetically sealed using a second tube slightly greater in diameter. In most resistors of this type, the change in resistance does not exceed 1 ppm/year.

The second factor affecting stability of precision resistors is the metallurgical stability of the alloy being used as the resistance element; any metallurgical change will be detrimental. All resistance alloys are single-phase, solid-solution alloys; thus, the changes in resistance that occur are relatively small but not insignificant. Changes in resistance are caused by internal changes such as long-range, order-disorder reactions in 71Ni-29Fe alloys, short-range order or clustering in quaternary nickel-chromium alloys, and even minor ordering in manganin alloys. Accordingly, resistance of these alloys is affected by heat treatment and by rates of cooling from heat treating temperatures. Power resistors that can operate at temperatures as high as 300 °C (570 °F) can in effect be heat treated during service. The net effect during service can be an increase in resistance for nickel-chromium alloys, a decrease for manganin, and either an increase or a decrease for nickel-iron alloys.

The third factor affecting stability of resistors is corrosion and/or oxidation. Corrosion of the resistance element will decrease its effective cross section, resulting in a corresponding increase in resistance. If the corrosive attack is selective, changes will occur in temperature coefficient of resistance and thermal electromotive force (emf) as well as in resistivity. These corrosive effects can be minimized by protecting the wire with an enamel or plastic coating. One relatively common source of corrosive attack, but one that is often overlooked, is flux residue at soldered or brazed joints. Another less obvious cause of instability is the presence of tin-containing solder. Intergranular stress corrosion, believed to originate during thermal stress-relieving treatments, can cause open circuits.

The fourth factor affecting the stability of enameled wire-wound resistors is humidity. The change in resistance is dependent on enamel thickness, wire diameter, and change in the amount of moisture to which the resistor is exposed. Increasing the moisture for a given resistor will cause a positive change in resistance, whereas decreasing the moisture causes a negative shift. This factor can be eliminated where it is physically possible to hermetically seal the resistor.

Combinations of these four factors--residual stresses, metallurgical instability, corrosion or oxidation, and humidity--account for the complex changes in resistance that often occur in resistors.

Solderability or Joining. The ease with which alloys can be soldered, brazed, or welded is an important consideration in selection of materials for precision resistors. Improperly brazed or soldered joints frequently cause resistance instability in the circuit. Metals to be soldered must be cleaned prior to tinning so that solder can completely wet the surfaces and maintain electrical continuity. For copper-nickel alloys this is relatively simple because protective oxide coatings are not formed on these alloys. Nickel-chromium alloys must be tinned immediately after cleaning and before an inherent protective oxide forms.

Pressure Coefficients of Resistance. The resistance value of a resistor may change if the hydrostatic pressure on the resistance element is changed; for manganin this change is approximately 23 pΩ/Ω · Pa (0.16 pΩ/Ω · psi). Sealed resistors can also be affected by changes in external pressure. In a double-wall, one-ohm resistor, for example, a change in pressure on the inner tube will cause a change in tube diameter, thus altering the length of wire wound on the tube. The magnitude of the resistance change depends in part on the thickness of the wall, and for commercial resistors is typically less than the hydrostatic pressure coefficient (PCR) of manganin. Unsealed resistors wound on mica cards containing air bubbles may have pressure coefficients several times greater than that predicted from the hydrostatic pressure coefficient of the alloy. This effect is important only if there is a large change in pressure, which would be most likely if there were a large change in elevation above sea level.

Thermostat Metals

A thermostat metal is a composite material (usually in the form of sheet or strip) that consists of two or more materials bonded together, of which one can be a nonmetal. Because the materials bonded together to form the composite differ in thermal expansion, the curvature of the composite is altered by changes in temperature: this is the fundamental characteristic of any thermostat metal. A thermostat metal is, therefore, a complete, self-contained transducing system capable of transforming heat directly into mechanical energy for control, indicating, or monitoring purposes.

In applications such as circuit breakers, thermal relays, motor overload protectors, and flashers, the change in temperature necessary for operation of the element is produced by the passage of current through the element itself--in other words, the charge is produced by I^2R heating. In certain other applications, any increase in the temperature of the thermostat element caused by I^2R heating is objectionable, and a thermostat metal with low electrical resistivity is required.

For circuit breakers and similar devices, there are thermostat metals that differ in electrical resistivity but that are similar in other properties. This allows a manufacturer to design a complete series of circuit breakers of different ratings in which the thermostat elements are all of the same size but have different electrical resistances. Resistivity is varied by incorporating a layer of a low-resistivity metal between outer layers of two other metals that have high resistivities and that differ widely in expansion coefficient.

In one series of commercial thermostat metals with resistivities ranging from 165 to 780 nΩ · m (100 to 470 Ω· circular-mil/ft) at 24 °C (75 °F), high-purity nickel is used for the intermediate layer. In a series with resistivities from 33 to 165 nΩ · m (20 to 100 Ω· circular-mil/ft), high-conductivity copper alloys are employed for the intermediate layer.

The use of a Mn-Cu-Ni alloy having a resistivity of 1745 nΩ · m (1050 Ω· circular-mil/ft) for one of the outer layers has extended the practical upper resistivity limit of thermostat metals to 1620 nΩ · m (975 Ω· circular-mil/ft) at 24 °C.

Tolerances on resistivity at a standard temperature vary from ±3 to ±10%, depending on the type of thermostat metal and its resistivity.

Approximately 30 different alloys are used to make over 50 different thermostat metals. Most of these 30 alloys are nickel-iron, nickel-chromium-iron, chromium-iron, high-copper, and high-manganese alloys.

Thermostat metals are available as strip or sheet in thicknesses ranging from 0.13 to 3.2 mm (0.005 to 0.125 in.) and widths from 0.5 to 300 mm (0.020 to 12 in.). They are easily formed into the required shapes. Thermostat metals usually are selected on the basis of the temperature range in which they are required to operate. They are available for various operating ranges between -185 and +540 °C (-300 and +1000 °F). Table 2 gives properties and typical bimetal combinations for several temperature ranges.

Table 2 Properties of thermostat metals frequently selected for some common service temperatures

Temperature range of maximum sensitivity		Composition		Resistivity at 24 °C (75 °F)		Flexivity[(a)]	
°C	**°F**	**High-expanding side**	**Low-expanding side**	**nΩ · m**	**Ω· circular-mil/ft**	**μm/m · °C**	**μin./in. · °F**
-20 to 150	0-300	75Fe-22Ni-3Cr	64Fe-36Ni	780	470	26.3	14.6
-20 to 200	0-400	75Fe-22Ni-3Cr	Pure Ni	160	95	8.3	4.6
		72Mn-18Cu-10Ni	64Fe-36Ni	1120	675	38.5	21.4
120-290	250-550	67Ni-30Cu-1.4Fe-1Mn	60Fe-40Ni	565	340	16.6	9.2
150-450	300-850	66.5Fe-22Ni-8.5Cr	50Fe-50Ni	580	350	11.2	6.2

(a) At 40-50 °C (100-300 °F). See ASTM B 106 for standard test method for determining flexivity of thermostat metals.

Heating Alloys

Resistance heating alloys are used in many varied applications--from small household appliances to large industrial process heating systems and furnaces. In appliances or industrial process heating, the heating elements are usually either open helical coils of resistance wire mounted with ceramic bushings in a suitable metal frame or enclosed metal-sheathed elements consisting of a smaller-diameter helical coil of resistance wire electrically insulated from the metal sheath by compacted refractory insulation. In industrial furnaces, elements often must operate continuously at temperatures as high as 1300 °C (2350 °F) for furnaces used in metal-treating industries, 1700 °C (3100 °F) for kilns used for firing ceramics and occasionally 2000 °C (3600 °F) or higher for special applications.

The primary requirements of materials used for heating elements are high melting point, high electrical resistivity, reproducible temperature coefficient of resistance, good oxidation resistance, absence of volatile components, and resistance to contamination. Other desirable properties are good elevated-temperature creep strength, high emissivity, low thermal expansion, and low modulus (both of which help minimize thermal fatigue), good resistance to thermal shock, and good strength and ductility at fabrication temperatures.

Table 3 gives physical and mechanical properties, and Table 4 presents recommended maximum operating temperatures for resistance heating materials for furnace applications. Of the four groups of materials listed in these tables, the first group (Ni-Cr and Ni-Cr-Fe alloys) serves by far the greatest number of applications.

Table 3 Typical properties of resistance heating materials

Basic composition	Resistivity(a), nΩ · m(b)	Average change in resistance(c), %, from 20 °C to:				Thermal expansion, μm/m · °C, from 20 °C to:			Tensile strength		Density	
		260 °C	**540 °C**	**815 °C**	**1095 °C**	**100 °C**	**540 °C**	**815 °C**	**MPa**	**ksi**	**g/cm^3**	**lb/in.^{3}**
Ni-Cr and Ni-Cr-Fe alloys												
78.5Ni-20Cr-1.5Si (80-20)	1080	4.5	7.0	6.3	7.6	13.5	15.1	17.6	655-1380	95-200	8.41	0.30
77.5Ni-20Cr-1.5Si-1Nb	1080	4.6	7.0	6.4	7.8	13.5	15.1	17.6	655-1380	95-200	8.41	0.30
68.5Ni-30Cr-1.5Si (70-30)	1180	2.1	4.8	7.6	9.8	12.2	. . .	. . .	825-1380	120-200	8.12	0.29
68Ni-20Cr-8.5Fe-2Si	1165	3.9	6.7	6.0	7.1	. . .	12.6	. . .	895-1240	130-180	8.33	0.30
60Ni-16Cr-22Fe-1.5Si	1120	3.6	6.5	7.6	10.2	13.5	15.1	17.6	655-1205	95-175	8.25	0.30
37Ni-21Cr-40Fe-2Si	1080	7.0	15.0	20.0	23.0	14.4	16.5	18.6	585-1135	85-165	7.96	0.288
35Ni-20Cr-43Fe-1.5Si	1000	8.0	15.4	20.6	23.5	15.7	15.7	. . .	550-1205	80-175	7.95	0.287
35Ni-20Cr-42.5Fe-1.5Si-1Nb	1000	8.0	15.4	20.6	23.5	15.7	15.7	. . .	550-1205	80-175	7.95	0.287
Fe-Cr-Al alloys												
83.5Fe-13Cr-3.25Al	1120	7.0	15.5	. . .	. . .	10.6	. . .	. . .	620-1035	90-150	7.30	0.26
81Fe-14.5Cr-4.25Al	1250	3.0	9.7	16.5	. . .	10.8	11.5	12.2	620-1170	90-170	7.28	0.26
73.5Fe-22Cr-4.5Al	1350	0.3	2.9	4.3	4.9	10.8	12.6	13.1	620-1035	90-150	7.15	0.26
72.5Fe-22Cr-5.5Al	1450	0.2	1.0	2.8	4.0	11.3	12.8	14.0	620-1035	90-150	7.10	0.26
Pure metals												
Molybdenum	52	110	238	366	508	4.8	5.8	. . .	690-2160	100-313	10.2	0.369
Platinum	105	85	175	257	305	9.0	9.7	10.1	345	50	21.5	0.775
Tantalum	125	82	169	243	317	6.5	6.6	. . .	345-1240	50-180	16.6	0.600
Tungsten	55	91	244	396	550	4.3	4.6	4.6	3380-6480	490-940	19.3	0.697
Nonmetallic heating-element materials												
Silicon carbide	995-1995	-33	-33	-28	-13	4.7	. . .	. . .	28	4	3.2	0.114
Molybdenum disilicide	370	105	222	375	523	9.2	. . .	. . .	185	27	6.24	0.225
$MoSi_2$ + 10% ceramic additives	270	167	370	597	853	13.1	14.2	14.8	. . .	. . .	5.6	0.202
Graphite	9100	-16	-18	-13	-8	1.3	. . .	. . .	1.8	0.26	1.6	0.057

(a)	At 20 °C (68 °F).
(b)	To convert to Ω· circular mil/ft, multiply by 0.6015.
(c)	Changes in resistance can vary somewhat, depending on cooling rate.

Table 4 Recommended maximum furnace operating temperatures for resistance heating materials

Basic composition, %	Approximate melting point		Maximum furnace operating temperature in air	
	°C	**°F**	**°C**	**°F**
Ni-Cr and Ni-Cr-Fe alloys				

78.5Ni-20Cr-1.5Si (80-20)	1400	2550	1150	2100
77.5Ni-20Cr-1.5Si-1Nb	1390	2540	. . .	. . .
68.5Ni-30Cr-1.5Si (70-30)	1380	2520	1200	2200
68Ni-20Cr-8.5Fe-2Si	1390	2540	1150	2100
60Ni-16Cr-22Fe-1.5Si	1350	2460	1000	1850
35Ni-30Cr-33.5Fe-1.5Si	1400	2550	. . .	. . .
35Ni-20Cr-43Fe-1.5Si	1380	2515	925	1700
35Ni-20Cr-42.5Fe-1.5Si-1Nb	1380	2515	. . .	. . .
Fe-Cr-Al alloys				
83.5Fe-13Cr-3.25Al	1510	2750	1050	1920
81Fe-14.5Cr-4.25Al	1510	2750	. . .	. . .
79.5Fe-15Cr-5.2Al	1510	2750	1260	2300
73.5Fe-22Cr-4.5Al	1510	2750	1280	2335
72.5Fe-22Cr-5.5Al	1510	2750	1375	2505
Pure metals				
Molybdenum	2610	4730	400(a)	750(a)
Platinum	1770	3216	1500	2750
Tantalum	3000	5400	500(a)	930(a)
Tungsten	3400	6150	300(a)	570(a)
Nonmetallic heating-element materials				
Silicon carbide	2410	4370	1600	2900
Molybdenum disilicide	(b)	(b)	1700-1800	3100-3270
$MoSi_2$ + 10% ceramic additives	(b)	(b)	1900	3450
Graphite	3650-3700(c)	6610-6690(c)	400(d)	750(d)

Element	Vacuum	Pure H_2	City gas
Mo	1650 °C (3000 °F)	1760 °C (3200 °F)	1700 °C (3100 °F)
Ta	2480 °C (4500 °F)	Not recommended	Not recommended
W	1650 °C (3000 °F)	2480 °C (4500 °F)	1700 °C (3100 °F)

(a) Recommended atmospheres for these metals are a vacuum of 10^{-4} to 10^{-5} mm Hg, pure hydrogen, and partly combusted city gas dried to a dew point of 4 °C (40 °F). For the recommended temperatures in these atmospheres, see the entries for Mo, Ta, and W at the end of this table.

(b) Decomposes before melting at 1740 °C (3165 °F) for $MoSi_2$, and 1825 °C (3315 °F) for $MoSi_2$ + 10% ceramic additives.

(c) Graphite volatilizes without melting at 3650 to 3700 °C (6610 to 6690 °F).

(d) At approximately 400 °C (750 °F) (threshold oxidation temperature), graphite undergoes a weight loss of 1% in 24 h in air. Graphite elements can be operated at surface temperatures up to 2205 °C (4000 °F) in inert atmospheres.

The ductile wrought alloys in the first group have properties that enable them to be used at both low and high temperatures in a wide variety of environments. The Fe-Cr-Al compositions (second group) are also ductile alloys. They play an important role in heaters for the higher temperature ranges, which are constructed to provide more effective mechanical support for the element. The pure metals that comprise the third group have much higher melting points. All of them except platinum are readily oxidized and are restricted to use in nonoxidizing environments. They are valuable for a limited range of application, primarily for service above 1370 °C (2500 °F). The cost of platinum prohibits its use except in small, special furnaces.

The fourth group, nonmetallic heating-element materials, are used at still higher temperatures. Silicon carbide can be used in oxidizing atmospheres at temperatures up to 1650 °C (3000 °F); three varieties of molybdenum disilicide are effective up to maximum temperatures of 1700, 1800, and 1900 °C (3100, 3270, and 3450 °F) in air. Molybdenum disilicide heating elements are gaining increased acceptance for use in industrial and laboratory furnaces. Among the desirable properties of molybdenum disilicide elements are excellent oxidation resistance, long life, constant electrical resistance, self-healing ability, and resistance to thermal shock. Nonmetallic heating elements described are considerably more fragile as compared to metal heating alloys.

Design of Resistance Heaters

Regardless of which heating alloy is selected, design of the heating element is important. One of the most important rules is to allow for unhindered expansion and contraction so as to avoid concentration of stresses as the temperature changes.

For service at lower temperatures, particularly from 400 to 600 °C (750 to 1100 °F), formed heating elements are used in ovens. In this construction, a heater support is made of two high-alloy rods spaced approximately 300 mm (12 in.) apart in a frame made of angle sections. The rods, whose length is determined by rated electrical input, contain spool insulators around which is wound a ribbon element made of a heating alloy. In a similar alternative construction, the ribbon element is replaced by a continuous helical coil of five gage or smaller wire.

Ribbon sizes for oven heaters range from 0.09 to 0.20 mm (0.0035 to 0.008 in.) thick and from 9.5 to 16 mm ($\frac{3}{8}$ to $\frac{5}{8}$ in.) wide. Oven heaters are rated to give maximum output at a watt density of approximately 8 kW/m^2 (5 W/in.^{2}). (Watt density is obtained by dividing total power input to the elements by total surface area of the heater.) For 120 or 240 V oven heaters operating under normal conditions, expected life of nickel-chromium elements in air is three to five years (depending on temperature, atmosphere, and cyclic conditions).

For furnace temperatures up to 1175 °C (2150 °F), sinuous loop elements generally are formed from ribbon having a width-to-thickness ratio of approximately 12 to 1 and dimensions varying from 0.76 to 3.2 mm (0.030 to 0.125 in.) in thickness and from 13 to 38 mm ($\frac{1}{2}$ to $1\frac{1}{2}$ in.) in width. Round rods of resistance material also can be formed into elements. Rod-type elements have been used by several furnace manufacturers.

Atmospheres

Based on element temperature, Table 5 rates serviceabilities of various heating-element materials as good, fair, or not recommended for the temperatures and atmospheres indicated. Types and compositions of standard furnace atmospheres are given in Table 6. Element temperatures are always higher than furnace control temperatures; the difference depends on watt-density loading on the element surface. Thus, when furnaces are operated near maximum element temperature in the more active atmospheres, watt-density loading should be lower and element cross-sectional area should be higher.

Table 5 Comparative life of heating-element materials in various furnace atmospheres

See Table 6 for atmosphere compositions.

Element material	Relative life and maximum operating temperature in							
	Oxidizing (air)	**Reducing: dry H_2 or type 501**	**Reducing: type 102 or 202**	**Reducing: type 301 or 402**	**Carburizing: type 307 or 309**	**Reducing or oxidizing, with sulfur**	**Reducing, with lead or zinc**	**Vacuum**
Ni-Cr and Ni-Cr-Fe alloys								
80Ni-20Cr	Good to 1150 °C	Good to 1175 °C	Fair to 1150 °C	Fair to 1000 °C	NR[(a)]	NR	NR	Good to 1150 °C
60Ni-16Cr-22Fe	Good to 1000 °C	Good to 1000 °C	Good to fair to 1000 °C	Fair to poor to 925 °C	NR	NR	NR	. . .
35Ni-20Cr-43Fe	Good to 925 °C	Good to 925 °C	Good to fair to 925 °C	Fair to poor to 870 °C	NR	Fair to 925 °C	Fair to 925 °C	. . .
Fe-Cr-Al alloys								
Fe, 22Cr, 5.8Al, 1Co	Good to 1400 °C	Fair to poor to 1150 °C[(b)]	Good to 1150 °C[(b)]	Fair to 1050 °C[(b)]	NR	Fair	NR	Good to 1150 °C[(b)]
22Cr, 5.3Al, bal Fe	Good to 1400 °C	Fair to poor to 1050 °C[(b)]	Good to 1050 °C[(b)]	Fair to 950 °C[(b)]	NR	Fair	NR	Good to 1050 °C[(b)]
Pure metals								
Molybdenum	NR[(c)]	Good to 1650 °C	NR	NR	NR	NR	NR	Good to 1650 °C
Platinum	Good to 1400 °C	NR	NR	NR	NR	NR	NR	. . .
Tantalum	NR	NR	NR	NR	NR	NR	NR	Good to 2500 °C
Tungsten	NR	Good to 2500 °C[(d)]	NR	NR	NR	NR	NR	Good to 1650 °C

Nonmetallic heating element materials								
Silicon carbide	Good to 1600 °C	Fair to poor to 1200 °C	Fair to 1375 °C	Fair to 1375 °C	NR	Good to 1375 °C	Good to 1375 °C	NR
Graphite	NR	Fair to 2500 °C	NR	Fair to 2500 °C	Fair to poor to 2500 °C	Fair to 2500 °C in reducing	Fair to 2500 °C	. . .
Molybdenum disilicide	Good to 1850 °C	1350 °C	1600 °C	1400 °C	1350 °C	. . .	. . .	. . .

NR, not recommended. Inert atmosphere of argon or helium can be used with all materials. Nitrogen is recommended only for the nickel-chromium group. Temperatures listed are element temperatures, not furnace temperatures.

(a) Special 80Ni-20Cr elements with ceramic protective coatings designated for low voltage (8 to 16 V) can be used.

(b) Must be oxidized first.

(c) Special molybdenum heating elements with $MoSi_2$ coating can be used in oxidizing atmospheres.

(d) Good with pure H_2 only

Table 6 Types and compositions of standard furnace atmospheres

See Table 5 for comparative life of heating elements in these atmospheres.

Type	Description	Composition, vol%					Typical dew point	
		N_2	**CO**	**CO_2**	**H_2**	**CH_4**	**°C**	**°F**
Reducing atmospheres								
102[(a)]	Exothermic unpurified	71.5	10.5	5.0	12.5	0.5	27	80
202	Exothermic purified	75.3	11.0	. . .	13.0	0.5	-40	-40
301	Endothermic	45.1	19.6	0.4	34.6	0.3	10	50
502	Charcoal	64.1	34.7	. . .	1.2	. . .	-29	-20
501	Dissociated ammonia	25	. . .	. . .	75	. . .	-51	-60
Carburizing atmospheres								
307	Endothermic + hydrocarbon	No standard composition					. . .	. . .
309	Endothermic + hydrocarbon + ammonia	No standard composition					. . .	. . .

(a) This atmosphere, refrigerated to obtain a dew point of 4 °C (40 °F), is widely used.

With the exception of molybdenum, tantalum, tungsten, and graphite, commonly used resistor materials have satisfactory life in air and in most other oxidizing atmospheres.

Atmosphere Contamination. Sulfur, if present, will appear as hydrogen sulfide in reducing atmospheres and as sulfur dioxide in oxidizing atmospheres. Sulfur contamination usually comes from one or more of the following sources: high-sulfur fuel gas used to generate the protective atmosphere, residues of sulfur-base cutting oil on the metal being processed; high-sulfur refractories, clays, or cements used for sealing carburizing boxes, and the metal being processed in the furnace. Sulfur is destructive to nickel-chromium and nickel-chromium-iron heating elements. Pitting and blistering of the alloy occur in oxidizing atmospheres, and a nickel-sulfur eutectic that melts at 645 °C (1190 °F) can form in any type of atmosphere. The higher the nickel content, the greater the attack. Therefore, if sulfur is present and cannot be eliminated, Fe-Cr-Al elements are preferred over those made of nickel-base alloys.

Lead and zinc contamination of a furnace atmosphere may come from the work being processed. This is a common occurrence in sintering furnaces for processing powder metallurgy parts. In the presence of a reducing atmosphere, lead will vaporize from leaded bronze powders (such as those used to make sintered bronze bushings) and attack the heating elements, forming lead chromate. Metallic lead vapors are even more harmful than sulfur to nickel-chromium alloys, and will cause severe damage to a heating element in a matter of hours if unfavorable conditions of concentration and temperature exist. Higher-nickel alloys are affected more than lower-nickel alloys. Elements made of 35Ni-20Cr-43.5Fe-1.5Si give satisfactory life for sintering lead-bearing bronze powders at 845 °C (1550 °F) in reducing atmospheres: 80Ni-20Cr elements give poor life in this application.

Zinc contamination results from zinc stearate used as a lubricant and binder when P/M compacts are pressed. The zinc stearate volatilizes when the compacts are heated and can carburize the heating element. (Brazing of nickel silvers, which contain at least 18% Zn, also results in a high concentration of zinc vapors in the furnace atmosphere.) Zinc vapors, which alloy with nickel-chromium heating elements and result in poor life, can be eliminated at the higher sintering temperatures by using a separate burn-off furnace at 650 °C (1200 °F), with heating elements protected by full muffle, by sheathing, or by a high-temperature ceramic protective coating. If these precautions are not feasible, silicon carbide elements (which are not affected by sulfur, lead, or zinc contamination) should be used at both low and high temperatures when contamination is anticipated.

Selected References

- R.A. Watson et al., Electrical Resistance Alloys, *Properties and Selections: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 822-839

Electrical Contact Materials

Introduction

ELECTRICAL CONTACTS are metal devices that make and break electrical circuits. If an ideal electrical contact material could be found, it would have high electrical conductivity to minimize the heat generated during passage of current; high thermal conductivity to dissipate both the resistive and arc heat developed; high reaction resistance to all environments in which it was to be used to avoid formation of insulating oxides, sulfides, and other compounds; and immunity o arcing damage on the making and breaking of electrical contact. The force required to close a contact made of this material would be low, as would the electrical resistance between mating members. The melting point of the material would be high enough to limit arc erosion, metal transfer, and welding or sticking, but it would also be low enough to increase resistance to reignition in switching. (When the melting point is high, contacts continue to heat gas in the contact gap after the current drops to zero, thus facilitating reignition.) The vapor pressure would be low to minimize arc erosion and metal transfer. Hardness would be high to provide good wear resistance, and yet ductility would be high enough to ensure ease of fabrication. Purity of the material would be maintainable at a level that ensures consistent performance. Neither the material nor any process step necessary to fabricate it would present an environmental hazard. Finally, the material would be available at low cost in any desired form.

Because no metal has all the desired properties, a wide variety of contact materials is required to accomplish the objectives of different contact applications. The economic choice of materials is usually a compromise between the various processing variables and the application requirements. Load conditions, service requirements, and ambient conditions present during the life of the unit must be considered in the selection of contact materials.

Failure Modes of Make-Break Contacts

In an electric make-break switching device, there are two different types of contacts: arcing contacts and sliding contacts. The arcing contact points, which usually consist of a pair of thin shaped slabs, perform the actual duty of making, carrying, and breaking the current. Arcing contacts differ from sliding contacts in that the moving member of the switching device travels perpendicular to the contact surfaces. As a result, arcs generated during opening and closing actions always strike and consequently damage the conducting surfaces.

Arcing, except in a circuit with an extremely low potential or low current, is a major factor--if not the main factor--causing failure of contact points.

When a pair of contacts opens in a live circuit, an arc is often generated between the contact pair, which remains until they are separated by a certain gap. Relatively less severe arcing occurs when the contacts close. Arcing also occurs when the moving contact bounces away from the stationary contact during closing. The arc causes contact erosion by blowing away the molten metal droplets, vaporizing the material, and transforming the metal to ion jets. Sometimes the material vaporizes from one contact and then condenses onto the other contact, thereby altering the surface configuration of both contacts. This is known as material transfer.

Welding. When a pair of contacts close, the arcs generated during closing and bouncing of a moving contact melt a small portion of both contacts. On reclosure, solidification of the molten material welds the contact pair in the same manner as fusion welding.

Another type of welding occurs after the contacts are made. To make a pair of contacts more conductive, a mechanical load is always applied on the contact pairs. Theoretically, the load could make two rigid contact surfaces touch at no more than three points. However, the touching points at both surfaces yield either elastically or plastically, resulting in larger areas of contact. These constricted regions carry the current through the contacts and form regions of high current density. Heat is generated in these areas and, if the temperature becomes high enough, the two contact points eventually are welded together. Occasionally, the strength of the weld exceeds the opening force of the switching device, resulting in catastrophic failure of the entire electrical system because the contacts fail to open on command.

Bridge Formation. When a pair of contacts opens, the contact area gradually decreases because of the gradual lessening of contact pressure. The continuous opening action causes the contact areas to reach a stage at which the current density of the constricted areas is so great that it melts the material in these regions. Continuous separation of the contact points now pulls the molten metal, forming a current-carrying bridge. The temperature of the molten bridge continues to rise as the contact points pull apart. It may become high enough to evaporate the material and finally break the circuit. This "bridge" phenomenon during the opening of a pair of contacts slightly damages the surfaces of the contacts and evaporates some of the bridge material. This generally results in pitting of one contact surface and buildup of material on the other; an uneven continuous transfer can eventually erode one of the contacts. Furthermore, the surface asperities from the continuous bridge formation can interlock the contact pair and interfere with their mechanical separation.

Oxidation of the contact surfaces, which can be accelerated by the heat from arcing, is a serious problem because most metallic oxide films are nonconductive or semiconductive. The oxide film may easily increase contact resistance. In high-current circuits, this can cause excessive contact heating. In low-voltage and low-current circuits, the oxide films can grow so thick that they completely insulate the contact surfaces before the contact bodies erode. This happens more frequently when a pair of contacts operates in a hostile environment such as a polluted industrial atmosphere. Condensed organic polymers also play a role in precious metal contacts at light loads. These polymers come from monomers, which evaporate from resins and are polymerized on the active catalytic metal surfaces of contacts.

Property Requirements for Make-Break Arcing Contacts

The four failure modes discussed in the section "Failure Modes of Make-Break Contacts" determine the requirements of materials for arcing contacts. In selecting a material, it is often necessary to reach a compromise that provides adequate properties without jeopardizing essential qualities of the component as a whole, such as reliability, life, and cost. The most important requirements are listed in the following paragraphs.

Electrical Conductivity. Because the conduction of electricity between the pair of contacts depends on only a few constricted spots, the higher the electrical conductivity, the less the amount of heat that will be generated by high current density in these spots.

Thermal Properties. High melting and boiling points decrease evaporation loss caused by high arcing heat. High thermal conductivity disperses the heat rapidly and quenches the arc.

Chemical Properties. Contact materials should be corrosion resistant so that insulating films (either oxides or other compounds) do not form easily when the contacts operate in a hostile environment.

Mechanical Properties. The major loads applied to a contact pair are the closing force and the impact between movable and stationary contact points during closing. An induced relative movement between two contact surfaces always exists when closing. In some devices, such as certain types of relays, a wiping motion is purposely designed into the device to destroy any oxide films that form. However, friction between wiping surfaces produces wear of the contacts upon repeated opening and closing. Generally, hard materials are more resistant to wear. However, hard materials often have high contact resistances and low thermal conductivities, both of which contribute to a greater tendency to contact welding. Hard materials also have high tensile strengths, which may or may not be advantageous in electrical contact applications.

Fabrication Properties. Contact materials should have the capability of being welded, brazed, or otherwise joined to backing materials. In addition, they should have sufficient malleability to enable them to be shaped, or they should be capable of being formed by powder metallurgy (P/M) techniques.

Sliding Contacts

The applications of sliding contacts are usually quite different from those of arcing contacts. Friction, contact temperature, mechanical considerations, and wear also are different.

The fundamental difference between arcing contacts and sliding contacts is that sliding contacts require films on the contact faces to facilitate sliding without seizure or galling; shear must occur within this film with only minor disturbance of both materials. A lubricant of some kind is always necessary. This can be provided by graphite if there is moisture present--such as in an environment having a dew point of -20 °C (-4 °F) or higher. Alternatively, lubrication can be provided by very thin oil films, although excessive oil vapor causes over filming. It can also be provided by molybdenum disulfide, and other chalcogenides of molybdenum, tungsten, and niobium. Oxygen, sulfur, and other contaminants cause increased filming.

In applications in air, a drop in voltage can result from an equilibrium between oxidation and filming (which tend to increase the drop) and fretting or film breakdown and cleaning action (which tend to decrease the drop). In the absence of lubricants, fretting and oxidation are most important. In inert or reducing gases, oxidation is largely eliminated, and the voltage drop decreases until counteracted by mechanical factors. Noble metals that are properly lubricated also minimize voltage drops in air.

Brush contacts generally contain an appreciable amount of metal if they are intended for use in low-voltage (<24 V) applications. Large quantities of brush contacts are used in automotive and related industries as starter brushes and auxiliary motor brushes; copper-graphite is the principal material. Silver-graphite brushes are used primarily in instruments and in outer space applications. Some silver-graphite brushes are used in seam welders and similar equipment.

Oxidation of sliding contacts is similar to that of arcing contacts, except that the surface disturbed by friction oxidizes more rapidly. In most applications in air, the metal surface generates a film that is a complex mixture of graphite, oxide, sulfide, and water, which tends to decrease the conducting area.

The surfaces generated on metal-graphite brushes as they wear are effective cleaning agents in that they abrade films and keep larger areas available for conduction. Even so, it is sometimes advisable to have additional abrasive material in the brushes to prevent over filming in critical atmospheres.

Because the major factor in friction is the shear strength of any film that is present, the composition of this film, as affected by atmospheric contaminants, is important.

Brush Materials. Considering the range of commercially available metal powders, graphites, other lubricants, and processing variables, there are unlimited possibilities for development of suitable brush materials. However, only a limited number of commercial grades have been developed, and most of these are copper-graphite (4 to 70% graphite) and silver-graphite (3 to 50% graphite) alloys (the latter alloys can also contain molybdenum disulfide).

More brush contacts are made from copper and copper alloys than from any other class of material. In applications where copper metals undergo substantial oxidation, silver metals can be used. Tungsten or, more rarely, molybdenum is used where a high melting point is required. Platinum, palladium, and gold are used where reliable closure with low force is required. Brushes clad or electroplated with precious metals and brushes made of sintered alloys are important for general applications in power-switching relays.

Interdependence Factors. When contacts are attached to a carrier, which is usually a copper alloy, the properties of the carrier material and the properties of the interface between contact and carrier (that is, the area of bond and the conductivity across the interface) are critical to ultimate performance. The contact carrier serves as a heat sink as well as a structural member and electrical conductor. The overall efficiency of the system depends on the contact, the contact carrier, and the method of attachment, all of which affect the size of the contact required for a specific application. To conserve precious metal, the contact materials, carrier material, and method of attachment must be optimized. Some high-strength, high-conductivity copper alloys are used for carriers because of their structural properties and resistance to softening at brazing temperatures.

The attachment method that provides minimum interface alloying, minimum softening of the carrier, and maximum bond area generally produces the best combination of properties for the contact system as a whole. Common attachment methods include brazing, resistance welding, percussion welding, and resistance induction torch welding. Welding methods provide the most localized heat input and therefore minimize softening of the carrier, which can occur during brazing methods. A more weldable backing such as steel, nickel, or monel is often clad to the precious metal to provide optimum welding compatibility with the carrier. Projections can also be coined or rolled into the contact backing to assist in welding.

Percussion welding does not require a special backing for attachment. However, percussion welding has fallen out of favor due to relatively high cost in comparison with brazing, welding, and mechanical attachment (riveting).

Commercial Contact Materials

Commercial materials for electrical contacts are divided into two categories based on their manufacturing methods: (a) wrought materials, which include both pure metals and alloys and (b) composite materials, which include powder metallurgy products and internally oxidized silver alloys.

Copper Metals

High electrical and thermal conductivities, low cost, and ease of fabrication account for the wide use of copper in electrical contacts, The main disadvantage of copper contacts is low resistance to oxidation and corrosion. In many applications, the voltage drop resulting from the film developed by normal oxidation and corrosion is acceptable. In some circuit breaker applications, the contacts are immersed in oil to prevent oxidation. In other applications, such as in drum controllers, sufficient wiping occurs to maintain fairly clean surfaces, thus providing a circuit of low resistance. In some applications, such as knife switches, plugs, and bolted connectors, contact surfaces are protected with grease or coatings of silver, nickel, or tin. In power circuits, where oxidation of copper is troublesome, contacts frequently are coated with silver. Vacuum-sealed circuit breakers use oxygen-free copper contacts (wrought or powder metal) for optimum electrical properties.

In air, copper does not provide high resistance to arcing, welding, or sticking. Where these characteristics are important, copper-tungsten or copper-graphite mixtures are used. However, when used in a helium atmosphere, a Cu-CdO contact performs similarly to an Ag-CdO contact. Copper alloys are used for high currents in vacuum interrupters.

Pure copper is relatively soft, anneals at low temperatures, and lacks the spring properties sometimes desired. Some copper alloys, harder than pure copper and having much better spring properties, are listed in Table 1. The annealing temperature of copper can be increased by additions of 0.25% Zn, 0.5% Cr, 0.03 to 0.06% Ag (10 to 20 oz per ton), or small amounts of finely dispersed metal oxides, such as Al_2O_3, with little loss of conductivity. Conversely, improved spring properties are obtained only at the expense of electrical conductivity. Precipitation-hardened alloys, dispersion-hardened alloys, and powder metal mixtures can provide a wide range of mechanical and electrical properties.

Table 1 Properties of copper metals used for electrical contacts

UNS number	Solidus temperature		Electrical conductivity, %IACS	Hardness		Tensile strength			
				OS035 temper	**H02 temper**	**OS035 temper**		**H02 temper**	
	°C	**°F**				**MPa**	**ksi**	**MPa**	**ksi**
C11000	1065	1950	100	40 HRF	40 HRB	220	32	290	42
C16200	1030	1886	90	54 HRF	64 HRB(a)	240	35	415(a)	60(a)
C17200	865	1590	15-33(b)	60 HRB(c)	93 HRB(d)	495(c)	72(c)	655(d)	95(d)
C23000	990	1810	37	63 HRF	65 HRB	285	41	395	57
C24000	965	1770	32	66 HRB	70 HRB	315	46	420	61
C27000	905	1660	27	68 HRF	70 HRB	340	49	420	61
C50500	1035	1900	48	60 HRF	59 HRB	276	40	365	53
C51000	975	1785	20	28 HRB	78 HRB	340	49	470	68
C52100	880	1620	13	80 HRF	84 HRB	400	58	525	76

(a) H04 temper.

(b) Depends on heat treatment.

(c) TB00 temper.

(d) TD02 temper

Applications. Copper-base metals are commonly used in plugs, jacks, sockets, connectors, and sliding contacts. Because of tarnish films, the contact force and amount of slide must be kept high to avoid excessive contact resistance and high levels of electrical noise. Yellow brass (C27000) is preferred for plugs and terminals because of its machinability. Phosphor bronze (C50500 or C51000) is preferred for thin socket and connector springs and for wiper-switch blades because of its strength and wear resistance. Nickel silver is sometimes preferred over yellow brass for relay and jack springs because of its high modulus of elasticity and strength, and also for its resistance to tarnishing and better appearance. Sometimes, copper alloy parts are nickel plated to improve surface hardness, reduce corrosion, and improve appearance. However, nickel carries a thin but hard oxide film that has high contact resistance; very high contact force and long slide are necessary to rupture the film. To maintain low levels of resistance and noise, copper metals should be plated or overlaid with a precious metal.

Silver Metals

Silver, in pure or alloyed form, is the most widely used material for a considerable range of make-and-break contacts (1 to 600 A). Mechanical properties and hardness of pure silver are improved by alloying, but its thermal and electrical conductivities are adversely affected. Figure 1 shows the effect of different alloying elements on the hardness and electrical resistivity of silver. Properties of the principal silver metals used for electrical contacts are given in Table 2. Silver is widely used in contacts that remain closed for long periods of time and, in the form of electroplate, is widely used as a coating for connection plugs and sockets. It is also used on contacts subject to occasional sliding, such as in rotary switches, and to a limited extent for low-resistance sliding contacts, such as slip rings.

Table 2 Properties of silver metals used for electrical contacts

Alloy	Solidus temperature		Electrical conductivity, %IACS	Hardness, HR15T		Tensile strength				Density, g/cm^3	Elongation in 50 mm or 2 in., %	
				Annealed	**Cold worked**	**Annealed**		**Cold worked**			**Annealed**	**Cold worked**
	°C	**°F**				**MPa**	**ksi**	**MPa**	**ksi**			
99.9Ag	960	1760	104	30	75	170	25	310	45	10.51	55	5
99.55Ag-0.25Mg-0.2Ni	. . .	. . .	70	61	77	207	30	345	50	10.34	35	6
99.47Ag-0.18Mg-0.2Ni-0.15Cu	. . .	. . .	75	64	84	. . .	. . .	. . .	. . .	10.38	. . .	. . .
99Ag-1Pd	. . .	. . .	79	44	76	180	26	324	47	10.14	42	3
97Ag-3Pd	977	1790	58	45	77	186	27	331	48	10.53	37	3
97Ag-3Pt	982	1800	45	45	77	172	25	324	47	10.17	37	3
92.5Ag-7.5Cu	821	1510	88	65	81	269	39	455	66	10.34	35	5
90Ag-10Au	971	1780	40	57	76	200	29	317	46	11.03	28	3
90Ag-10Cu	775	1430	85	70	83	276	40	517	75	10.31	32	4
90Ag-10Pd	1000	1830	27	63	80	234	34	365	53	10.57	31	3
86.8Ag-5.5Cd-0.2Ni-7.5Cu	. . .	. . .	43	72	85	276	40	517	75	10.10	43	3
85Ag-15Cd	877	1610	35	51	83	193	28	400	58	10.17	55	5
77Ag-22.6Cd-0.4Ni	. . .	. . .	31	50	85	241	35	469	68	10.31	55	4
75Ag-24.5Cu-0.5Ni	. . .	. . .	75	78	85	310	45	552	80	10.00	32	4
72Ag-28Cu	775	1430	84	79	85	365	53	552	80	9.95	20	5
60Ag-23Pd-12Cu-5Ni	. . .	. . .	11	86	93	517	78	758	110	10.51	22	3

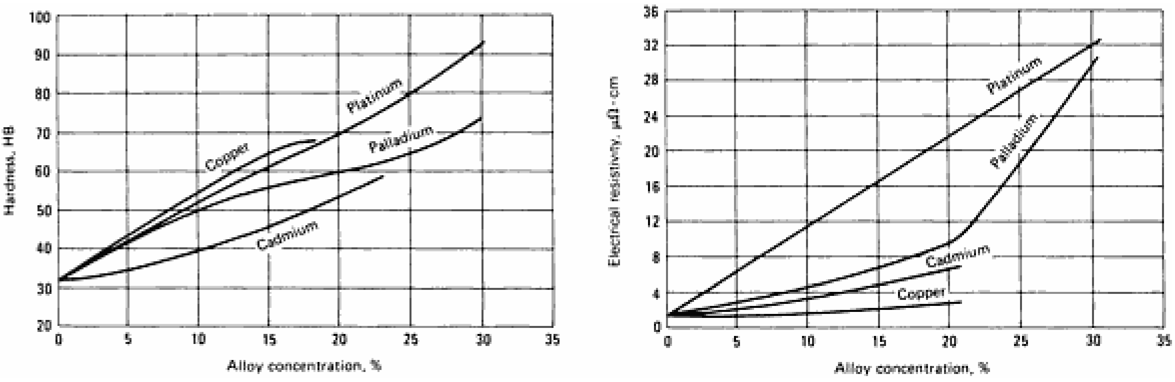

Fig. 1 Hardness and electrical resistivity versus alloy content for silver alloy contacts

Electrical and Thermal Conductivity. Because silver has the highest electrical and thermal conductivities of all metals at room temperature, it can carry high currents without excessive heating, even when dimensions of the contacts are only moderate. Although good thermal conductivity is desired once the contact is in service, such conductivity increases the difficulty of assembly welding unless a higher resistance layer is added by cladding.

In component assemblies, migration of silver through and around electrical insulation can cause failure of the insulation. When in contact with certain materials, such as phenol fiber, and when under electric potential, silver migrates ionically through or across the insulating material, producing thread-like connections that lower the resistance across the insulation. This reduces insulating qualities, and the reduction is even greater if moisture is present in the atmosphere. Insulators must be designed with care to avoid this hazard.

Oxidation Resistance. Silver is used instead of copper chiefly because of its resistance to oxidation in air. In general, silver oxide is not a problem on silver contacts, whether or not the contacts make and break the circuit. However, silver oxide can be produced by exposure to ozone, as well as by other methods. This oxide has high resistivity, is decomposed slowly on heating at approximately 175 °C (350 °F), is decomposed rapidly at approximately 350 °C (650 °F), and is removed by arcing. This "self-cleaning" characteristic is most unusual among metals and is a chief reason for the attraction of silver as a contact material.

Silver is vulnerable to attack by sulfur or sulfide gases in the presence of moisture. The resulting sulfide film can produce significant contact resistance, particularly where contact force, voltage, or current is low. Direct current brings silver ions from the matrix into the sulfide where they form connecting bridges. Therefore, particularly at high direct current, the film becomes somewhat conducting. The resistance of a silver sulfide film decreases as temperature increases--Ag_2S decomposes slowly at 360 °C (680 °F) and more rapidly at higher temperatures. In addition, the film can increase erosion and entrap dust.

Limitations of Silver Contacts. Silver will provide a fairly long contact life for make-break contacts and will handle up to 600 A. In pure silver contacts, difficulties sometimes arise from transfer of metal from one electrode to the other, which leads to the formation of buildups on one contact surface and holes in the other. When used in direct current (dc) circuits, silver contacts are subject to ultimate failure by mechanical sticking as a direct result of metal transfer. The direction of transfer is generally from the positive contact to the negative, but under the influence of arcing, the direction can be reversed. With high currents or inductive loads, it may be desirable to shunt the load with a resistance-capacitance protection network to reduce erosion.

When arcing produces a glow discharge in air, the rate of erosion of silver is unusually high because of a chemical interaction with air to form $AgNO_2$.

For low resistance and low noise levels, the design of the contact device must provide sufficient force and slide to break through any silver sulfide film and maintain film-free, metal-to-metal contact at the interface. Connectors should have high slide force and several newtons normal force. Rotary switches that have up to 490 mN (0.11 lbf) normal force and considerable slide should have a protective coating of grease to reduce sulfiding and to remove abrasive particles. In low-noise transmission circuits, silver should not be used on relay and other butting contacts that have less than 195 mN (0.044 lbf) force; other precious-metal coatings, such as gold or palladium, should be used instead of silver.

A silver sulfide film has a characteristic voltage drop of several tenths of a volt. Where this drop is tolerable, silver contacts will provide reliable contact closure. Failure to close, however, can be greater than with other precious metal contacts because of impacted dirt, with a sulfide film acting as a dirt catcher.

For many applications, silver is too soft to give acceptable mechanical wear. Alloying additions of copper, cadmium, platinum, palladium, gold, and other elements are effective in increasing the hardness and modifying the contact behavior of silver. These additions do, however, lower both the electrical conductivity and the oxidation resistance relative to pure silver.

Gold Metals

Pure gold has unsurpassed resistance to oxidation and sulfidation, but a low melting point and susceptibility to erosion limit its use in electrical contacts to situations where the current is not more than 0.5 A. Although oxide and sulfide films do not form on gold, a carbonaceous deposit is sometimes formed when a gold contact is operated in the presence of organic vapors. The resistance of this film can be several ohms.

When gold is used in contact with palladium or rhodium, very low contact resistances have been reported.

The low hardness of gold can be increased by alloying with copper, silver, palladium, and platinum, but usage is necessarily restricted to low-current applications because of the low melting point.

Properties of gold and its alloys are listed in Table 3. If low tarnish rates and low contact resistance are to be preserved, the gold content should not be less than approximately 70%.

Table 3 Properties of gold metals used for electrical contacts

Alloy	Solidus temperature		Electrical conductivity, %IACS	Hardness, HR15T		Tensile strength				Density, g/cm^3
						Annealed		**Cold worked**		
	°C	**°F**		**Annealed**	**Cold worked**	**MPa**	**ksi**	**MPa**	**ksi**	
99Au	1085	1985	74	40	65	. . .	. . .	. . .	. . .	19.36
90Au-10Cu	932	1710	16	76	91	400	58	705	102	17.18
75Au-25Ag	1029	1885	17	50	77	. . .	. . .	. . .	. . .	15.96
71.5Au-14.5Cu-8.5Pt-4Ag-1Zn	925	1700	11	88	96	. . .	. . .	. . .	. . .	15.9
72.5Au-14Cu-8.5Pt-4Ag-1Zn	954	1750	10	88	96	. . .	. . .	. . .	. . .	16.11
72Au-26.2Ag-1.8Ni	. . .	. . .	14	61	81	230	33	345	50	15.56
71Au-5Ag-9Pt-15Cu	. . .	. . .	8	88.5	75(a)	700	101	1170	170	16.02
69Au-25Ag-6Pt	1029	1885	10	70	84	275	40	415	60	15.92
50Au-50Ag	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	13.59

(a) Rockwell 15N

Precious Metals of the Platinum Group

Platinum and palladium are the two most important metals of the platinum group. These metals have a high resistance to tarnishing, and therefore provide reliable contact closure for relays and other devices having contact forces of less than 490 mN (0.110 lbf). Their high melting points, low vapor pressure, and resistance to arcing make them suitable for contacts that close and open the load, particularly in the range up to 1 A. The low electrical and thermal conductivities of these metals, as well as their cost, generally exclude them from use at currents above approximately 5 A.

Palladium has an arcing limit only slightly less than that of platinum and gives comparable performance in relays for telephones and similar services handling 1 A or less. Palladium is a satisfactory substitute for platinum in these applications. Table 4 lists properties of platinum, palladium, and platinum and palladium alloys.

Table 4 Properties of platinum and palladium metals used for electrical contacts

Alloy	Solidus temperature		Electrical conductivity(a), %IACS	Hardness, HR15T		Tensile strength				Density, g/cm^3	Elongation(a) in 50 mm (2 in.), %
						Annealed		Cold worked			
	°C	°F		Annealed	Cold worked	MPa	ksi	MPa	ksi		
99.9Pt	1770	3220	15	60	73	138	20	241	35	21.45	35
95Pt-5Ru	1775	3230	5	84	89	414	60	793	115	20.57	18
92Pt-8Ru	. . .	. . .	4	86	91	483	70	896	130	20.27	15
90Pt-10Ir	1780	3240	7	87	92	379	55	620	90	21.52	12
89Pt-11Ru	1815	3300	4	91	96	586	85	1034	150	19.96	12
86Pt-14Ru	1843	3350	3	93	99	655	95	1172	170	19.06	10
85Pt-15Ir	1787	3250	6	90	95	517	75	827	120	21.52	12
80Pt-20Ir	1810	3290	5	93	97	689	100	1000	145	21.63	12
75Pt-25Ir	1819	3310	5	95	98	862	125	1172	170	21.68	10
73.4Pt-18.4Pd-8.2Ru	. . .	. . .	4	90	92	517	75	862	125	17.77	12
65Pt-35Ir	1899	3450	4	97	99	965	140	1344	195	21.80	8
99.9Pd	1554	2830	16	62	78	193	28	324	47	12.17	28
95Pd-5Ru	1593	2900	8	79	89	372	54	517	75	12.00	15
89Pd-11Ru	1650	3000	6	85	92	483	70	689	100	12.03	13
72Pd-26Ag-2Ni	1382	2520	4	82	90	469	68	689	100	11.52	13
60Pd-40Ag	1338	2440	4	65	91	372	54	689	100	11.30	28
60Pd-40Cu	1200	2190	8	82	92	565	82	1331	193	10.67	20
35Pd-9.5Pt-9Au-14Cu-32.5Ag	1085	1985	5	90	94	689	100	1034	150	11.63	18
35Pd-10Pt-10Au-14Cu-30Ag	1015	1860	5	90	98	827	120	1240	180	11.8	20
44Pd-38Ag-16Cu-1Pt-1Zn	1032	1890	7	91	96	758	110	1205	175	10.8	15

(a) For material in annealed condition

Corrosion Resistance. Platinum has it high resistance to corrosion, including resistance to oxidation, sulfidation, and salt water. It will not form a stable oxide at any temperature.

Palladium is resistant to oxidation at ordinary temperatures. If heated above 350 °C (660 °F), it will oxidize slowly to form an oxide that is stable at room temperature. However, the oxide is decomposed promptly on heating to 800 °C (1470 °F) or by arcing. The oxide is not considered to be a significant factor in the reliability of closure of telephone-type relays.

The presence of organic vapors in the contact area can seriously influence the life and reliability of electrical contacts, particularly the low-force precious metal contacts universally employed in high-reliability, low-noise circuits. The damaging organic vapors can arise from coil forms, wire coatings, insulation, soldering flux, potting and sealing compounds, and other organics in associated electrical equipment, as well as from external sources.

Precious Metal Overlays

Silver, gold, rhodium, and, to a lesser extent, platinum and palladium are employed in clad and electroplated contacts. Electrodeposition and cladding compete for many of the same applications. Clad overlays are favored because of their lower porosity, but electrodeposits are slightly less expensive for those applications requiring a very thin layer of precious metal. Electrodeposits frequently have higher hardness than the annealed wrought material; rhodium, which has a deposit hardness in excess of 600 HV in the annealed condition, is an outstanding example. High hardness accounts for the superior wear resistance of electroplated rhodium where rubbing or wiping occurs. Even at a thickness of 0.13 to 0.50 μm (5 to 20 μin.) over silver or base-metal contacts, rhodium improves wear resistance and minimizes tarnishing.

Electroplated gold is employed on silver contacts to minimize tarnishing. Nickel underlayers (barrier coats) are used to prevent migration of silver through the gold plate. Recent studies indicate that migration of silver along nickel grain boundaries is rapid at high temperatures. Hence, a nickel barrier coat is questionable for high-temperature applications. Other work in this area has disclosed that palladium can be substituted for gold as a protective coating for extension of shelf life. Electroplated gold also is used on palladium contacts to minimize polymer formation in dry circuits. However, gold electrodeposits on both silver and palladium contacts soon wear off if the contacts wipe, rub, or arc.

Electroplated silver is sometimes applied to copper-base materials to make less expensive components. Electroplated silver is slightly harder than annealed wrought silver. Palladium and platinum electroplated on silver have improved tarnish resistance. Platinum, palladium, and gold electroplates are used on silver to prevent the development of conducting filaments in insulating supports.

Clad overlays are used extensively in applications requiring precious-metal thicknesses from 0.025 to 1.3 mm (0.001 to 0.050 in.). These thicknesses cannot be obtained by electroplating. These applications include electromechanical devices operating in current ranges where arcing and subsequent erosion are likely to occur. In these devices, sufficient precious metal must be available to survive the erosion that will occur over the required device cycle life.

Tungsten and Molybdenum

Most tungsten and molybdenum contacts are made in the form of composites with silver or copper as the other principal component (see the subsection "Composite Materials"). Tungsten, which was one of the earliest metals other than copper and silver adopted for electrical contact applications, has the highest boiling point (5930 °C, or 10,700 °F) and melting point (3110 °C, or 5625 °F) of all metals; it also has very high hardness at both room and elevated temperatures. Therefore, as a contact material, it offers excellent resistance to mechanical wear and electrical erosion. Its main disadvantages are low corrosion resistance and low electrical conductivity (31% IACS). After a short period of operation, an oxidized film will build up on tungsten contacts, resulting in very high contact resistance. Considerable force is required to break through the film, but high pressure and considerable impact cause little damage to the underlying metal because of its high hardness. Tungsten contacts are used in switching devices with closing forces of more than 20 N (4.5 lbf) and in circuits with high voltages and currents not more than 5 A, such as automotive ignitions, vibrators, horns, voltage regulators, magnetos, and electric razors. In low-voltage direct current (dc) devices, tungsten is always used as the negative contact, and is paired with a positive contact made of precious metal.

Tungsten rods or strips that are consolidated by swaging or rolling from sintered powder compacts have very poor ductility. They cannot be cold worked, in contrast to other contact materials. Tungsten disks are usually cut from rods or punched from strips and then brazed directly to functional parts such as breaker arms, brackets, or springs.

Properties such as grain size, grain configuration, and the degree of fibrous structure, which affect contact behavior, are controlled by using special swaging methods and annealing cycles. Tungsten disks usually are supplied with a ground finish, but they can also be electrochemically polished to obtain high-luster surfaces.

The high boiling and melting points of molybdenum--5560 °C (10,040 °F) and 2610 °C (4730 °F), respectively--are second only to those of tungsten and rhenium. Molybdenum is not used as widely as tungsten because it oxidizes more readily and erodes faster on arcing than tungsten. Nevertheless, because the density of molybdenum (10.2 g/cm^3 or 0.369 lb/in.^{3}) is about half that of tungsten (19.3 g/cm^3, or 0.697 lb/in.^{3}), use of molybdenum is advantageous where mass is important. The cost of molybdenum by volume is also lower.

In addition to use in make-break contacts, molybdenum is widely used for mercury switches because it is not attacked, but only wetted by mercury.

Like tungsten, molybdenum strips and sheets are made by swaging or rolling sintered powder compacts. Disks made from rods or sheets are brazed to blanks or other structural components.

Aluminum

Aluminum is generally a poor contact material because it oxidizes readily, but it is used in some contact applications because of its good electrical and mechanical properties, availability, and cost. Aluminum 1350 is used for some contact applications.

Where aluminum is used in contacting joints, it should be plated or clad with copper, silver, or tin. Aluminum should never be used for power applications where arcing is present. For instance, if aluminum contacts were substituted for silver in a motor starter, an explosion due to noninterruption of current on motor-starter de-energization would probably occur on load interruption.

Composite Materials

There are three major groups of composite materials made by P/M or internal oxidation (IO) methods, or combinations of P/M and IO: refractory metal or carbide-base, silver-base, and copper-base. Table 5 lists the various types of contact materials and their respective manufacturing methods. Contacts based on refractory metals or their carbides include Mo-Ag, WC-Ag, W-Ag, WC-Cu, and W-C-Ag systems. Silver-base composites can be divided into two types: type 1 uses a pure element (nickel, tungsten, or molybdenum) or graphite as the dispersed phase; and type 2 composites use semirefractory oxides (CdO, SnO_2, or ZnO) as the dispersed phase. In both types, hardness increases and conductivities decrease as the volume fraction of dispersed phase increases. The silver-cadmium oxide group of electrical contact materials is the most widely used of all the silver semirefractory contact materials. Copper-base contacts contain tungsten as the dispersed phase.

Table 5 Properties of selected composite electrical contact materials

Nominal composition, %	Manufacturing method(a)	Density, g/cm^3	Electrical conductivity, %IACS	Hardness	Tensile strength	
					MPa	**ksi**
Molybdenum-silver						
90Ag-10Mo	PSR	10.38	65-68	35-40 HRB	. . .	. . .
65Ag-35Mo	PSR	10.30	55-64	49-55 HRB	. . .	. . .
35Ag-65Mo	INF	10.00-10.08	40-45	82-92 HRB	. . .	. . .
10Ag-90Mo	INF	10.13	27-30	97-102 HRB	. . .	. . .
Silver/cadmium oxide						
85Ag-15CdO	PSR	8.60-9.58	55-75	35 HRF(b)	83(b)	12(b)
	PSE	9.90-10.06	55-75	57 HRF(b)	193(b)	28(b)
				80 HRF(c)	241(b)	35(c)
	IO	10.06	65	50 HRF(b)	207(b)	30(b)
				85 HRF(c)	269(c)	39(c)
	PPSE	10.06	72	70 HRF (b)	276(b)	40(b)
				90 HRF(c)	331(c)	48(c)
Silver-graphite						
99Ag-1C	PSR	9.40-10.12	87-99	24-36 HRF(b)	162(b)	23.5(b)
				68-69 HRF(c)	241(c)	35(c)
95Ag-5C	PSR	8.30-8.68	55-62	25 HRF(d)	. . .	. . .
	PSE	8.84	75	40 HRF(d)	. . .	. . .
90Ag-10C	PSR	6.30-7.20	43-53	13 HRF(b)	. . .	. . .
				30 HRF(c)	. . .	. . .
Silver-nickel						
90Ag-10Ni	PSR	9.70-10.32	75-90	35 HRF(b)	172(c)	25(c)
				89 HRF(c)	. . .	. . .
60Ag-40Ni	PSR	8.90-9.60	44-47	40 HR30T(b)	241(b)	35(b)
				92 HR30T(b)	414(c)	60(c)
	PSE	9.60	60	46 HR30T(b)	. . .	. . .
40Ag-60Ni	PSR	8.80	32	35 HR30T(b)	. . .	. . .
				97 HR(c)	. . .	. . .
	PSE	9.30	40	68 HR30T(b)	. . .	. . .
20Ag-80Ni	PSR	8.00	21	35 HR30T(b)	. . .	. . .
Silver/tin oxide						
92Ag-8SnO$_2$	PSE	10.00	88	58 HV(b)	205-230	30-33.5
				92 HV(c)	. . .	. . .
90Ag-10SnO$_2$	PSE	9.97	82	64 HV(b)	215(b)	31(b)
				98 HV(c)	. . .	. . .
88Ag-12SnO$_2$	PSE	9.68	72	72 HV(b)	. . .	. . .
				105 HV(c)	. . .	. . .
Tungsten carbide-silver						
65Ag-35WC	INF	11.53-11.85	55-60	50-65 HRB	272	39.5
	PSR	11.10-11.80	50-60	50-62 HRB	. . .	. . .
50Ag-50WC	INF	12.12-12.50	43-52	75-85 HRB	276	40
35Ag-65WC	INF	12.90-13.18	30-37	95-105 HRB	. . .	. . .
Tungsten-silver						
90Ag-10W	PSR	10.30-11.20	90-95	20-33 HRB	. . .	. . .

65Ag-35W	PSR	12.1	68	80 HV(b)	. . .	. . .
				90 HV(c)	. . .	. . .
35Ag-65W	INF	14.20-14.77	45-53	80-93 HRB	. . .	. . .
	PS	13.90-14.20	47-50	85-87 HRB	. . .	. . .
	PSR	14.65-14.74	47-50	55-65 HRB(c)	. . .	. . .
10Ag-90W	PSR	17.25	29-35	95-105 HRB	379	55
Tungsten carbide-copper						
50Cu	INF	11.00-11.27	42-47	90-100 HRF	. . .	. . .
30Cu	INF	12.65	30	38 HRC	. . .	. . .
Tungsten-copper						
75Cu-25W	PSR	9.45-10.00	50-79	35-60 HRB	. . .	. . .
50Cu-50W	INF	11.90-11.96	45-63	60-81 HRB	. . .	. . .
35Cu-65W	INF	13.35	54	83-93 HRB	. . .	. . .
20Cu-80W	INF	15.20	30-40	95-105 HRB	758	110
Tungsten-graphite-silver						
46Ag-53W-1C	PSR	12.85	55	85 HRB	. . .	. . .
45Ag-50W-5C	PSR	10.60	37-43	45-55 HRB	. . .	. . .

(a) PSR, press-sinter-repress; INF, press-sinter-infiltrate; PS, press-sinter; PSE, press-sinter-extrude; IO, internal oxidation; PPSE, preoxidize-press-sinter-extrude.

(b) Annealed.

(c) Cold worked

Composite Manufacturing Methods

Infiltration is used exclusively for making refractory metal and carbide-base composite contact materials. Metal powder or carbide powder is first blended to the desired composition with or without a small amount of binder to impart green strength, then is pressed and sintered into a skeleton of the required shape. Silver or copper is then infiltrated into the pores of the skeleton. This method produces the most densified composites, generally 97% or more of theoretical density. Complete densification is not possible because of the presence of some closed pores in the sintered skeleton. After infiltration, the contact is sometimes chemically or electrochemically etched so that only pure silver appears on the surface. The contact thus treated has better corrosion resistance and performs better in the early stages of use.

Press-Sinter. For small refractory-metal contacts (not exceeding approximately 25 mm, or 1 in., in diameter), a high-density material can be obtained by pressing a blended powder of exact final composition into shape and then sintering it at the melting temperature of the low-melting-point component (liquid-phase sintering). In some cases, an activating agent such as nickel, cobalt, or iron is added to improve the sintering effect on the refractory metal particles. For this process, powders of much finer particle size are required so that more bonding surface exists. However, the skeleton formed by this process is weaker than that formed by the infiltration process. Formation of the skeleton usually shrinks the apparent volume of the refractory portion of the composition, thus bleeding out the molten component onto the surface of the finished contact.

The press-sinter-repress process is used for all categories of contact materials, especially those in the silver-base category. Blended powders of the correct composition are compacted to the required shape and then sintered. Afterward, the material is further densified by a second pressing (repressing). Sometimes the properties can be modified by a second sintering or annealing. The versatility of this process makes it applicable for contacts of any configuration and of any material. However, it is difficult to obtain material with as high a density as is obtained with other processes. Material thus produced also may have weak bonding between particles.

Press-Sinter-Extrude Process. Blended powder of final composition is pressed into an ingot and sintered. The ingot is then extruded into wires, slabs, or other desired shapes. The extruded material can be subsequently worked by rolling, swaging, or drawing. Material made by this method is usually fully dense.

The press-sinter-extrude process is used mostly for silver-base composites. Other processes used for manufacturing silver-base composite contacts are direct extrusion or direct rolling of loose powder. Although they appear to be uncommon, they are economically feasible if the equipment is properly designed and built.

Internal Oxidation. Silver-base composites with dispersed metal oxides can be produced by internal oxidation. In this process, a silver alloy (such as a silver-cadmium alloy) is first cast into ingots, which are rolled into strips or fabricated further into the finished product form. The silver-alloy material is then heated in air or oxygen, so that the oxygen diffuses into the alloy and forms metal oxide particles (such as CdO in the case of a silver-cadmium alloy) dispersed in the silver matrix.

Internal oxidation is used in the production of a substantial portion of Ag-CdO composites. The initial silver-cadmium alloy can be internally oxidized either in strip or finished product form. The silver-cadmium alloy is heated between 800 and 900 °C (1470 and 1650 °F) in a furnace with air, oxygen-enriched air, or pressurized oxygen. Under this condition, the oxygen species diffuse into the silver-cadmium alloy and oxidize the cadmium species. Upon the completion of the oxidation, the cross section of the material will display a microstructure of cadmium oxide particles embedded in a silver matrix. Contact parts are punched from the strip and then coined into required shapes.

The preoxidized-press-sinter-extrude process is used exclusively for making silver-cadmium oxide (Ag-CdO) material. Alloys are reduced to small particles in the shape of flakes, slugs, or shredded foil. These particles are oxidized and then consolidated with the press-sinter-extrude process. Material made by this method is more uniform than the same material made by conventional internal oxidation. Mechanical properties are superior to those of the same material made by the press-sinter-repress method.

Coprecipitation. Conventional blending or mechanical mixing of silver and cadmium oxide powders begins by dissolving the proper amounts of silver and cadmium metals in nitric acid. Compounds of silver and cadmium coprecipitate from the solution when the pH value of the solution is changed by adding either hydroxide or carbonate solutions. During subsequent calcination at approximately 500 °C (930 °F), the compound mixture decomposes to form a mixture of silver and cadmium oxide. Alkali-metal content can be controlled in the ppm range by adequate washing. Controlled amounts of sodium, potassium, and lithium may enhance electrical life. Excessive amounts of these elements can lead to rapid erosion, restrike, and generally poor electrical life. Depending on device design, the range can be from 10 to 300 ppm. Contacts are consolidated from this mixture by conventional P/M methods. The microstructure of contacts made by this method displays a finer particle size and a more uniformly dispersed CdO phase than material made by conventional blending.

Selected References

- Y-S. Shen et al., Electrical Contact Materials, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 840-868

Commercial Contact Materials

Commercial materials for electrical contacts are divided into two categories based on their manufacturing methods: (a) wrought materials, which include both pure metals and alloys and (b) composite materials, which include powder metallurgy products and internally oxidized silver alloys.

Copper Metals

High electrical and thermal conductivities, low cost, and ease of fabrication account for the wide use of copper in electrical contacts, The main disadvantage of copper contacts is low resistance to oxidation and corrosion. In many applications, the voltage drop resulting from the film developed by normal oxidation and corrosion is acceptable. In some circuit breaker applications, the contacts are immersed in oil to prevent oxidation. In other applications, such as in drum controllers, sufficient wiping occurs to maintain fairly clean surfaces, thus providing a circuit of low resistance. In some applications, such as knife switches, plugs, and bolted connectors, contact surfaces are protected with grease or coatings of silver, nickel, or tin. In power circuits, where oxidation of copper is troublesome, contacts frequently are coated with silver. Vacuum-sealed circuit breakers use oxygen-free copper contacts (wrought or powder metal) for optimum electrical properties.

In air, copper does not provide high resistance to arcing, welding, or sticking. Where these characteristics are important, copper-tungsten or copper-graphite mixtures are used. However, when used in a helium atmosphere, a Cu-CdO contact performs similarly to an Ag-CdO contact. Copper alloys are used for high currents in vacuum interrupters.

Pure copper is relatively soft, anneals at low temperatures, and lacks the spring properties sometimes desired. Some copper alloys, harder than pure copper and having much better spring properties, are listed in Table 1. The annealing temperature of copper can be increased by additions of 0.25% Zn, 0.5% Cr, 0.03 to 0.06% Ag (10 to 20 oz per ton), or small amounts of finely dispersed metal oxides, such as Al_2O_3, with little loss of conductivity. Conversely, improved spring properties are obtained only at the expense of electrical conductivity. Precipitation-hardened alloys, dispersion-hardened alloys, and powder metal mixtures can provide a wide range of mechanical and electrical properties.

Table 1 Properties of copper metals used for electrical contacts

UNS number	Solidus temperature		Electrical conductivity, %IACS	Hardness		Tensile strength			
				OS035 temper	**H02 temper**	**OS035 temper**		**H02 temper**	
	°C	**°F**				**MPa**	**ksi**	**MPa**	**ksi**
C11000	1065	1950	100	40 HRF	40 HRB	220	32	290	42
C16200	1030	1886	90	54 HRF	64 HRB$^{(a)}$	240	35	415$^{(a)}$	60$^{(a)}$
C17200	865	1590	15-33$^{(b)}$	60 HRB$^{(c)}$	93 HRB$^{(d)}$	495$^{(c)}$	72$^{(c)}$	655$^{(d)}$	95$^{(d)}$
C23000	990	1810	37	63 HRF	65 HRB	285	41	395	57
C24000	965	1770	32	66 HRB	70 HRB	315	46	420	61
C27000	905	1660	27	68 HRF	70 HRB	340	49	420	61
C50500	1035	1900	48	60 HRF	59 HRB	276	40	365	53
C51000	975	1785	20	28 HRB	78 HRB	340	49	470	68
C52100	880	1620	13	80 HRF	84 HRB	400	58	525	76

(a) H04 temper.

(b) Depends on heat treatment.

(c) TB00 temper.

(d) TD02 temper

Applications. Copper-base metals are commonly used in plugs, jacks, sockets, connectors, and sliding contacts. Because of tarnish films, the contact force and amount of slide must be kept high to avoid excessive contact resistance and high levels of electrical noise. Yellow brass (C27000) is preferred for plugs and terminals because of its machinability. Phosphor bronze (C50500 or C51000) is preferred for thin socket and connector springs and for wiper-switch blades because of its strength and wear resistance. Nickel silver is sometimes preferred over yellow brass for relay and jack springs because of its high modulus of elasticity and strength, and also for its resistance to tarnishing and better appearance. Sometimes, copper alloy parts are nickel plated to improve surface hardness, reduce corrosion, and improve appearance. However, nickel carries a thin but hard oxide film that has high contact resistance; very high contact force and long slide are necessary to rupture the film. To maintain low levels of resistance and noise, copper metals should be plated or overlaid with a precious metal.

Silver Metals

Silver, in pure or alloyed form, is the most widely used material for a considerable range of make-and-break contacts (1 to 600 A). Mechanical properties and hardness of pure silver are improved by alloying, but its thermal and electrical conductivities are adversely affected. Figure 1 shows the effect of different alloying elements on the hardness and electrical resistivity of silver. Properties of the principal silver metals used for electrical contacts are given in Table 2. Silver is widely used in contacts that remain closed for long periods of time and, in the form of electroplate, is widely used as a coating for connection plugs and sockets. It is also used on contacts subject to occasional sliding, such as in rotary switches, and to a limited extent for low-resistance sliding contacts, such as slip rings.

Table 2 Properties of silver metals used for electrical contacts

Alloy	Solidus temperature		Electrical conductivity, %IACS	Hardness, HR15T		Tensile strength				Density, g/cm^3	Elongation in 50 mm or 2 in., %	
				Annealed	**Cold worked**	**Annealed**		**Cold worked**			**Annealed**	**Cold worked**
	°C	**°F**				**MPa**	**ksi**	**MPa**	**ksi**			
99.9Ag	960	1760	104	30	75	170	25	310	45	10.51	55	5
99.55Ag-0.25Mg-0.2Ni	. . .	. . .	70	61	77	207	30	345	50	10.34	35	6
99.47Ag-0.18Mg-0.2Ni-0.15Cu	. . .	. . .	75	64	84	. . .	. . .	. . .	. . .	10.38	. . .	. . .

99Ag-1Pd	. . .	. . .	79	44	76	180	26	324	47	10.14	42	3
97Ag-3Pd	977	1790	58	45	77	186	27	331	48	10.53	37	3
97Ag-3Pt	982	1800	45	45	77	172	25	324	47	10.17	37	3
92.5Ag-7.5Cu	821	1510	88	65	81	269	39	455	66	10.34	35	5
90Ag-10Au	971	1780	40	57	76	200	29	317	46	11.03	28	3
90Ag-10Cu	775	1430	85	70	83	276	40	517	75	10.31	32	4
90Ag-10Pd	1000	1830	27	63	80	234	34	365	53	10.57	31	3
86.8Ag-5.5Cd-0.2Ni-7.5Cu	. . .	. . .	43	72	85	276	40	517	75	10.10	43	3
85Ag-15Cd	877	1610	35	51	83	193	28	400	58	10.17	55	5
77Ag-22.6Cd-0.4Ni	. . .	. . .	31	50	85	241	35	469	68	10.31	55	4
75Ag-24.5Cu-0.5Ni	. . .	. . .	75	78	85	310	45	552	80	10.00	32	4
72Ag-28Cu	775	1430	84	79	85	365	53	552	80	9.95	20	5
60Ag-23Pd-12Cu-5Ni	. . .	. . .	11	86	93	517	78	758	110	10.51	22	3

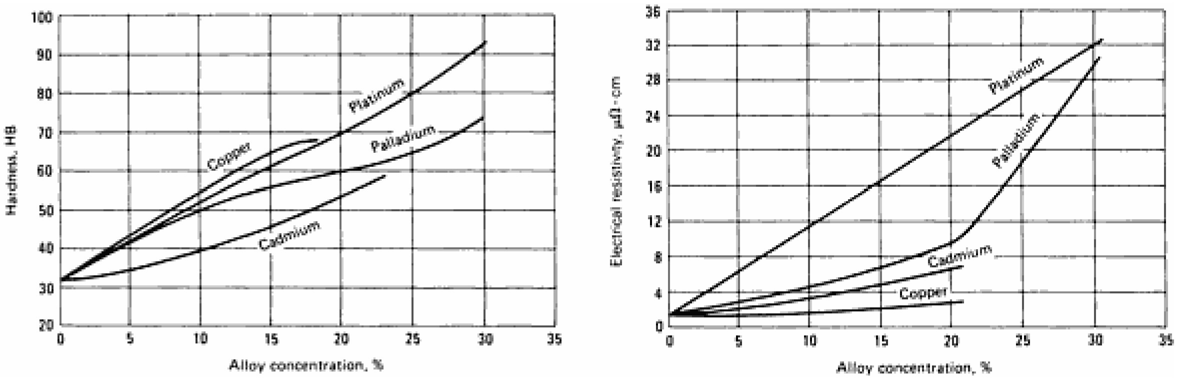

Fig. 1 Hardness and electrical resistivity versus alloy content for silver alloy contacts

Electrical and Thermal Conductivity. Because silver has the highest electrical and thermal conductivities of all metals at room temperature, it can carry high currents without excessive heating, even when dimensions of the contacts are only moderate. Although good thermal conductivity is desired once the contact is in service, such conductivity increases the difficulty of assembly welding unless a higher resistance layer is added by cladding.

In component assemblies, migration of silver through and around electrical insulation can cause failure of the insulation. When in contact with certain materials, such as phenol fiber, and when under electric potential, silver migrates ionically through or across the insulating material, producing thread-like connections that lower the resistance across the insulation. This reduces insulating qualities, and the reduction is even greater if moisture is present in the atmosphere. Insulators must be designed with care to avoid this hazard.

Oxidation Resistance. Silver is used instead of copper chiefly because of its resistance to oxidation in air. In general, silver oxide is not a problem on silver contacts, whether or not the contacts make and break the circuit. However, silver oxide can be produced by exposure to ozone, as well as by other methods. This oxide has high resistivity, is decomposed slowly on heating at approximately 175 °C (350 °F), is decomposed rapidly at approximately 350 °C (650 °F), and is removed by arcing. This "self-cleaning" characteristic is most unusual among metals and is a chief reason for the attraction of silver as a contact material.

Silver is vulnerable to attack by sulfur or sulfide gases in the presence of moisture. The resulting sulfide film can produce significant contact resistance, particularly where contact force, voltage, or current is low. Direct current brings silver ions from the matrix into the sulfide where they form connecting bridges. Therefore, particularly at high direct current, the film becomes somewhat conducting. The resistance of a silver sulfide film decreases as temperature increases--Ag_2S decomposes slowly at 360 °C (680 °F) and more rapidly at higher temperatures. In addition, the film can increase erosion and entrap dust.

Limitations of Silver Contacts. Silver will provide a fairly long contact life for make-break contacts and will handle up to 600 A. In pure silver contacts, difficulties sometimes arise from transfer of metal from one electrode to the other, which leads to the formation of buildups on one contact surface and holes in the other. When used in direct current (dc) circuits, silver contacts are subject to ultimate failure by mechanical sticking as a direct result of metal transfer. The direction of transfer is generally from the positive contact to the negative, but under the influence of arcing, the direction can be reversed. With high currents or inductive loads, it may be desirable to shunt the load with a resistance-capacitance protection network to reduce erosion.

When arcing produces a glow discharge in air, the rate of erosion of silver is unusually high because of a chemical interaction with air to form $AgNO_2$.

For low resistance and low noise levels, the design of the contact device must provide sufficient force and slide to break through any silver sulfide film and maintain film-free, metal-to-metal contact at the interface. Connectors should have high slide force and several newtons normal force. Rotary switches that have up to 490 mN (0.11 lbf) normal force and considerable slide should have a protective coating of grease to reduce sulfiding and to remove abrasive particles. In low-noise transmission circuits, silver should not be used on relay and other butting contacts that have less than 195 mN (0.044 lbf) force; other precious-metal coatings, such as gold or palladium, should be used instead of silver.

A silver sulfide film has a characteristic voltage drop of several tenths of a volt. Where this drop is tolerable, silver contacts will provide reliable contact closure. Failure to close, however, can be greater than with other precious metal contacts because of impacted dirt, with a sulfide film acting as a dirt catcher.

For many applications, silver is too soft to give acceptable mechanical wear. Alloying additions of copper, cadmium, platinum, palladium, gold, and other elements are effective in increasing the hardness and modifying the contact behavior of silver. These additions do, however, lower both the electrical conductivity and the oxidation resistance relative to pure silver.

Gold Metals

Pure gold has unsurpassed resistance to oxidation and sulfidation, but a low melting point and susceptibility to erosion limit its use in electrical contacts to situations where the current is not more than 0.5 A. Although oxide and sulfide films do not form on gold, a carbonaceous deposit is sometimes formed when a gold contact is operated in the presence of organic vapors. The resistance of this film can be several ohms.

When gold is used in contact with palladium or rhodium, very low contact resistances have been reported.

The low hardness of gold can be increased by alloying with copper, silver, palladium, and platinum, but usage is necessarily restricted to low-current applications because of the low melting point.

Properties of gold and its alloys are listed in Table 3. If low tarnish rates and low contact resistance are to be preserved, the gold content should not be less than approximately 70%.

Table 3 Properties of gold metals used for electrical contacts

Alloy	Solidus temperature		Electrical conductivity, %IACS	Hardness, HR15T		Tensile strength				Density, g/cm^3
						Annealed		**Cold worked**		
	°C	**°F**		**Annealed**	**Cold worked**	**MPa**	**ksi**	**MPa**	**ksi**	
99Au	1085	1985	74	40	65	. . .	. . .	. . .	. . .	19.36
90Au-10Cu	932	1710	16	76	91	400	58	705	102	17.18
75Au-25Ag	1029	1885	17	50	77	. . .	. . .	. . .	. . .	15.96
71.5Au-14.5Cu-8.5Pt-4Ag-1Zn	925	1700	11	88	96	. . .	. . .	. . .	. . .	15.9
72.5Au-14Cu-8.5Pt-4Ag-1Zn	954	1750	10	88	96	. . .	. . .	. . .	. . .	16.11
72Au-26.2Ag-1.8Ni	. . .	. . .	14	61	81	230	33	345	50	15.56
71Au-5Ag-9Pt-15Cu	. . .	. . .	8	88.5	75(a)	700	101	1170	170	16.02

69Au-25Ag-6Pt	1029	1885	10	70	84	275	40	415	60	15.92
50Au-50Ag	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	13.59

(a) Rockwell 15N

Precious Metals of the Platinum Group

Platinum and palladium are the two most important metals of the platinum group. These metals have a high resistance to tarnishing, and therefore provide reliable contact closure for relays and other devices having contact forces of less than 490 mN (0.110 lbf). Their high melting points, low vapor pressure, and resistance to arcing make them suitable for contacts that close and open the load, particularly in the range up to 1 A. The low electrical and thermal conductivities of these metals, as well as their cost, generally exclude them from use at currents above approximately 5 A.

Palladium has an arcing limit only slightly less than that of platinum and gives comparable performance in relays for telephones and similar services handling 1 A or less. Palladium is a satisfactory substitute for platinum in these applications. Table 4 lists properties of platinum, palladium, and platinum and palladium alloys.

Table 4 Properties of platinum and palladium metals used for electrical contacts

Alloy	Solidus temperature		Electrical conductivity(a), %IACS	Hardness, HR15T		Tensile strength				Density, g/cm^3	Elongation(a) in 50 mm (2 in.), %
						Annealed		**Cold worked**			
	°C	**°F**		**Annealed**	**Cold worked**	**MPa**	**ksi**	**MPa**	**ksi**		
99.9Pt	1770	3220	15	60	73	138	20	241	35	21.45	35
95Pt-5Ru	1775	3230	5	84	89	414	60	793	115	20.57	18
92Pt-8Ru	. . .	. . .	4	86	91	483	70	896	130	20.27	15
90Pt-10Ir	1780	3240	7	87	92	379	55	620	90	21.52	12
89Pt-11Ru	1815	3300	4	91	96	586	85	1034	150	19.96	12
86Pt-14Ru	1843	3350	3	93	99	655	95	1172	170	19.06	10
85Pt-15Ir	1787	3250	6	90	95	517	75	827	120	21.52	12
80Pt-20Ir	1810	3290	5	93	97	689	100	1000	145	21.63	12
75Pt-25Ir	1819	3310	5	95	98	862	125	1172	170	21.68	10
73.4Pt-18.4Pd-8.2Ru	. . .	. . .	4	90	92	517	75	862	125	17.77	12
65Pt-35Ir	1899	3450	4	97	99	965	140	1344	195	21.80	8
99.9Pd	1554	2830	16	62	78	193	28	324	47	12.17	28
95Pd-5Ru	1593	2900	8	79	89	372	54	517	75	12.00	15
89Pd-11Ru	1650	3000	6	85	92	483	70	689	100	12.03	13
72Pd-26Ag-2Ni	1382	2520	4	82	90	469	68	689	100	11.52	13
60Pd-40Ag	1338	2440	4	65	91	372	54	689	100	11.30	28
60Pd-40Cu	1200	2190	8	82	92	565	82	1331	193	10.67	20
35Pd-9.5Pt-9Au-14Cu-32.5Ag	1085	1985	5	90	94	689	100	1034	150	11.63	18
35Pd-10Pt-10Au-14Cu-30Ag	1015	1860	5	90	98	827	120	1240	180	11.8	20
44Pd-38Ag-16Cu-1Pt-1Zn	1032	1890	7	91	96	758	110	1205	175	10.8	15

(a) For material in annealed condition

Corrosion Resistance. Platinum has it high resistance to corrosion, including resistance to oxidation, sulfidation, and salt water. It will not form a stable oxide at any temperature.

Palladium is resistant to oxidation at ordinary temperatures. If heated above 350 °C (660 °F), it will oxidize slowly to form an oxide that is stable at room temperature. However, the oxide is decomposed promptly on heating to 800 °C (1470 °F) or by arcing. The oxide is not considered to be a significant factor in the reliability of closure of telephone-type relays.

The presence of organic vapors in the contact area can seriously influence the life and reliability of electrical contacts, particularly the low-force precious metal contacts universally employed in high-reliability, low-noise circuits. The damaging organic vapors can arise from coil forms, wire coatings, insulation, soldering flux, potting and sealing compounds, and other organics in associated electrical equipment, as well as from external sources.

Precious Metal Overlays

Silver, gold, rhodium, and, to a lesser extent, platinum and palladium are employed in clad and electroplated contacts. Electrodeposition and cladding compete for many of the same applications. Clad overlays are favored because of their lower porosity, but electrodeposits are slightly less expensive for those applications requiring a very thin layer of precious metal. Electrodeposits frequently have higher hardness than the annealed wrought material; rhodium, which has a deposit hardness in excess of 600 HV in the annealed condition, is an outstanding example. High hardness accounts for the superior wear resistance of electroplated rhodium where rubbing or wiping occurs. Even at a thickness of 0.13 to 0.50 μm (5 to 20 μin.) over silver or base-metal contacts, rhodium improves wear resistance and minimizes tarnishing.

Electroplated gold is employed on silver contacts to minimize tarnishing. Nickel underlayers (barrier coats) are used to prevent migration of silver through the gold plate. Recent studies indicate that migration of silver along nickel grain boundaries is rapid at high temperatures. Hence, a nickel barrier coat is questionable for high-temperature applications. Other work in this area has disclosed that palladium can be substituted for gold as a protective coating for extension of shelf life. Electroplated gold also is used on palladium contacts to minimize polymer formation in dry circuits. However, gold electrodeposits on both silver and palladium contacts soon wear off if the contacts wipe, rub, or arc.

Electroplated silver is sometimes applied to copper-base materials to make less expensive components. Electroplated silver is slightly harder than annealed wrought silver. Palladium and platinum electroplated on silver have improved tarnish resistance. Platinum, palladium, and gold electroplates are used on silver to prevent the development of conducting filaments in insulating supports.

Clad overlays are used extensively in applications requiring precious-metal thicknesses from 0.025 to 1.3 mm (0.001 to 0.050 in.). These thicknesses cannot be obtained by electroplating. These applications include electromechanical devices operating in current ranges where arcing and subsequent erosion are likely to occur. In these devices, sufficient precious metal must be available to survive the erosion that will occur over the required device cycle life.

Tungsten and Molybdenum

Most tungsten and molybdenum contacts are made in the form of composites with silver or copper as the other principal component (see the subsection "Composite Materials"). Tungsten, which was one of the earliest metals other than copper and silver adopted for electrical contact applications, has the highest boiling point (5930 °C, or 10,700 °F) and melting point (3110 °C, or 5625 °F) of all metals; it also has very high hardness at both room and elevated temperatures. Therefore, as a contact material, it offers excellent resistance to mechanical wear and electrical erosion. Its main disadvantages are low corrosion resistance and low electrical conductivity (31% IACS). After a short period of operation, an oxidized film will build up on tungsten contacts, resulting in very high contact resistance. Considerable force is required to break through the film, but high pressure and considerable impact cause little damage to the underlying metal because of its high hardness. Tungsten contacts are used in switching devices with closing forces of more than 20 N (4.5 lbf) and in circuits with high voltages and currents not more than 5 A, such as automotive ignitions, vibrators, horns, voltage regulators, magnetos, and electric razors. In low-voltage direct current (dc) devices, tungsten is always used as the negative contact, and is paired with a positive contact made of precious metal.

Tungsten rods or strips that are consolidated by swaging or rolling from sintered powder compacts have very poor ductility. They cannot be cold worked, in contrast to other contact materials. Tungsten disks are usually cut from rods or punched from strips and then brazed directly to functional parts such as breaker arms, brackets, or springs.

Properties such as grain size, grain configuration, and the degree of fibrous structure, which affect contact behavior, are controlled by using special swaging methods and annealing cycles. Tungsten disks usually are supplied with a ground finish, but they can also be electrochemically polished to obtain high-luster surfaces.

The high boiling and melting points of molybdenum--5560 °C (10,040 °F) and 2610 °C (4730 °F), respectively--are second only to those of tungsten and rhenium. Molybdenum is not used as widely as tungsten because it oxidizes more readily and erodes faster on arcing than tungsten. Nevertheless, because the density of molybdenum (10.2 g/cm^3 or 0.369 lb/in.^{3}) is about half that of tungsten (19.3 g/cm^3, or 0.697 lb/in.^{3}), use of molybdenum is advantageous where mass is important. The cost of molybdenum by volume is also lower.

In addition to use in make-break contacts, molybdenum is widely used for mercury switches because it is not attacked, but only wetted by mercury.

Like tungsten, molybdenum strips and sheets are made by swaging or rolling sintered powder compacts. Disks made from rods or sheets are brazed to blanks or other structural components.

Aluminum

Aluminum is generally a poor contact material because it oxidizes readily, but it is used in some contact applications because of its good electrical and mechanical properties, availability, and cost. Aluminum 1350 is used for some contact applications.

Where aluminum is used in contacting joints, it should be plated or clad with copper, silver, or tin. Aluminum should never be used for power applications where arcing is present. For instance, if aluminum contacts were substituted for silver in a motor starter, an explosion due to noninterruption of current on motor-starter de-energization would probably occur on load interruption.

Composite Materials

There are three major groups of composite materials made by P/M or internal oxidation (IO) methods, or combinations of P/M and IO: refractory metal or carbide-base, silver-base, and copper-base. Table 5 lists the various types of contact materials and their respective manufacturing methods. Contacts based on refractory metals or their carbides include Mo-Ag, WC-Ag, W-Ag, WC-Cu, and W-C-Ag systems. Silver-base composites can be divided into two types: type 1 uses a pure element (nickel, tungsten, or molybdenum) or graphite as the dispersed phase; and type 2 composites use semirefractory oxides (CdO, SnO_2, or ZnO) as the dispersed phase. In both types, hardness increases and conductivities decrease as the volume fraction of dispersed phase increases. The silver-cadmium oxide group of electrical contact materials is the most widely used of all the silver semirefractory contact materials. Copper-base contacts contain tungsten as the dispersed phase.

Table 5 Properties of selected composite electrical contact materials

Nominal composition, %	Manufacturing method(a)	Density, g/cm^3	Electrical conductivity, %IACS	Hardness	Tensile strength	
					MPa	**ksi**
Molybdenum-silver						
90Ag-10Mo	PSR	10.38	65-68	35-40 HRB	. . .	. . .
65Ag-35Mo	PSR	10.30	55-64	49-55 HRB	. . .	. . .
35Ag-65Mo	INF	10.00-10.08	40-45	82-92 HRB	. . .	. . .
10Ag-90Mo	INF	10.13	27-30	97-102 HRB	. . .	. . .
Silver/cadmium oxide						
85Ag-15CdO	PSR	8.60-9.58	55-75	35 HRF(b)	83(b)	12(b)
	PSE	9.90-10.06	55-75	57 HRF(b)	193(b)	28(b)
				80 HRF(c)	241(b)	35(c)
	IO	10.06	65	50 HRF(b)	207(b)	30(b)
				85 HRF(c)	269(c)	39(c)
	PPSE	10.06	72	70 HRF (b)	276(b)	40(b)
				90 HRF(c)	331(c)	48(c)
Silver-graphite						
99Ag-1C	PSR	9.40-10.12	87-99	24-36 HRF(b)	162(b)	23.5(b)
				68-69 HRF(c)	241(c)	35(c)
95Ag-5C	PSR	8.30-8.68	55-62	25 HRF(d)	. . .	. . .
	PSE	8.84	75	40 HRF(d)	. . .	. . .
90Ag-10C	PSR	6.30-7.20	43-53	13 HRF(b)	. . .	. . .
				30 HRF(c)	. . .	. . .
Silver-nickel						
90Ag-10Ni	PSR	9.70-10.32	75-90	35 HRF(b)	172(c)	25(c)
				89 HRF(c)	. . .	. . .
60Ag-40Ni	PSR	8.90-9.60	44-47	40 HR30T(b)	241(b)	35(b)
				92 HR30T(b)	414(c)	60(c)

	PSE	9.60	60	46 HR30T$^{(b)}$	. . .	. . .
40Ag-60Ni	PSR	8.80	32	35 HR30T$^{(b)}$	. . .	. . .
				97 HR$^{(c)}$	. . .	. . .
	PSE	9.30	40	68 HR30T$^{(b)}$	. . .	. . .
20Ag-80Ni	PSR	8.00	21	35 HR30T$^{(b)}$	. . .	. . .
Silver/tin oxide						
92Ag-8SnO$_2$	PSE	10.00	88	58 HV$^{(b)}$	205-230	30-33.5
				92 HV$^{(c)}$	. . .	. . .
90Ag-10SnO$_2$	PSE	9.97	82	64 HV$^{(b)}$	215$^{(b)}$	31$^{(b)}$
				98 HV$^{(c)}$	. . .	. . .
88Ag-12SnO$_2$	PSE	9.68	72	72 HV$^{(b)}$	. . .	. . .
				105 HV$^{(c)}$	. . .	. . .
Tungsten carbide-silver						
65Ag-35WC	INF	11.53-11.85	55-60	50-65 HRB	272	39.5
	PSR	11.10-11.80	50-60	50-62 HRB	. . .	. . .
50Ag-50WC	INF	12.12-12.50	43-52	75-85 HRB	276	40
35Ag-65WC	INF	12.90-13.18	30-37	95-105 HRB	. . .	. . .
Tungsten-silver						
90Ag-10W	PSR	10.30-11.20	90-95	20-33 HRB	. . .	. . .
65Ag-35W	PSR	12.1	68	80 HV$^{(b)}$	. . .	. . .
				90 HV$^{(c)}$	. . .	. . .
35Ag-65W	INF	14.20-14.77	45-53	80-93 HRB	. . .	. . .
	PS	13.90-14.20	47-50	85-87 HRB	. . .	. . .
	PSR	14.65-14.74	47-50	55-65 HRB$^{(c)}$	. . .	. . .
10Ag-90W	PSR	17.25	29-35	95-105 HRB	379	55
Tungsten carbide-copper						
50Cu	INF	11.00-11.27	42-47	90-100 HRF	. . .	. . .
30Cu	INF	12.65	30	38 HRC	. . .	. . .
Tungsten-copper						
75Cu-25W	PSR	9.45-10.00	50-79	35-60 HRB	. . .	. . .
50Cu-50W	INF	11.90-11.96	45-63	60-81 HRB	. . .	. . .
35Cu-65W	INF	13.35	54	83-93 HRB	. . .	. . .
20Cu-80W	INF	15.20	30-40	95-105 HRB	758	110
Tungsten-graphite-silver						
46Ag-53W-1C	PSR	12.85	55	85 HRB	. . .	. . .
45Ag-50W-5C	PSR	10.60	37-43	45-55 HRB	. . .	. . .

(a) PSR, press-sinter-repress; INF, press-sinter-infiltrate; PS, press-sinter; PSE, press-sinter-extrude; IO, internal oxidation; PPSE, preoxidize-press-sinter-extrude.

(b) Annealed.

(c) Cold worked

Composite Manufacturing Methods

Infiltration is used exclusively for making refractory metal and carbide-base composite contact materials. Metal powder or carbide powder is first blended to the desired composition with or without a small amount of binder to impart green strength, then is pressed and sintered into a skeleton of the required shape. Silver or copper is then infiltrated into the pores of the skeleton. This method produces the most densified composites, generally 97% or more of theoretical density. Complete densification is not possible because of the presence of some closed pores in the sintered skeleton. After infiltration, the contact is sometimes chemically or electrochemically etched so that only pure silver appears on the surface. The contact thus treated has better corrosion resistance and performs better in the early stages of use.

Press-Sinter. For small refractory-metal contacts (not exceeding approximately 25 mm, or 1 in., in diameter), a high-density material can be obtained by pressing a blended powder of exact final composition into shape and then sintering it at the melting temperature of the low-melting-point component (liquid-phase sintering). In some cases, an activating agent such as nickel, cobalt, or iron is added to improve the sintering effect on the refractory metal particles. For this process, powders of much finer particle size are required so that more bonding surface exists. However, the skeleton formed by this process is weaker than that formed by the infiltration process. Formation of the skeleton usually shrinks the apparent volume of the refractory portion of the composition, thus bleeding out the molten component onto the surface of the finished contact.

The press-sinter-repress process is used for all categories of contact materials, especially those in the silver-base category. Blended powders of the correct composition are compacted to the required shape and then sintered. Afterward, the material is further densified by a second pressing (repressing). Sometimes the properties can be modified by a second sintering or annealing. The versatility of this process makes it applicable for contacts of any configuration and of any material. However, it is difficult to obtain material with as high a density as is obtained with other processes. Material thus produced also may have weak bonding between particles.

Press-Sinter-Extrude Process. Blended powder of final composition is pressed into an ingot and sintered. The ingot is then extruded into wires, slabs, or other desired shapes. The extruded material can be subsequently worked by rolling, swaging, or drawing. Material made by this method is usually fully dense.

The press-sinter-extrude process is used mostly for silver-base composites. Other processes used for manufacturing silver-base composite contacts are direct extrusion or direct rolling of loose powder. Although they appear to be uncommon, they are economically feasible if the equipment is properly designed and built.

Internal Oxidation. Silver-base composites with dispersed metal oxides can be produced by internal oxidation. In this process, a silver alloy (such as a silver-cadmium alloy) is first cast into ingots, which are rolled into strips or fabricated further into the finished product form. The silver-alloy material is then heated in air or oxygen, so that the oxygen diffuses into the alloy and forms metal oxide particles (such as CdO in the case of a silver-cadmium alloy) dispersed in the silver matrix.

Internal oxidation is used in the production of a substantial portion of Ag-CdO composites. The initial silver-cadmium alloy can be internally oxidized either in strip or finished product form. The silver-cadmium alloy is heated between 800 and 900 °C (1470 and 1650 °F) in a furnace with air, oxygen-enriched air, or pressurized oxygen. Under this condition, the oxygen species diffuse into the silver-cadmium alloy and oxidize the cadmium species. Upon the completion of the oxidation, the cross section of the material will display a microstructure of cadmium oxide particles embedded in a silver matrix. Contact parts are punched from the strip and then coined into required shapes.

The preoxidized-press-sinter-extrude process is used exclusively for making silver-cadmium oxide (Ag-CdO) material. Alloys are reduced to small particles in the shape of flakes, slugs, or shredded foil. These particles are oxidized and then consolidated with the press-sinter-extrude process. Material made by this method is more uniform than the same material made by conventional internal oxidation. Mechanical properties are superior to those of the same material made by the press-sinter-repress method.

Coprecipitation. Conventional blending or mechanical mixing of silver and cadmium oxide powders begins by dissolving the proper amounts of silver and cadmium metals in nitric acid. Compounds of silver and cadmium coprecipitate from the solution when the pH value of the solution is changed by adding either hydroxide or carbonate solutions. During subsequent calcination at approximately 500 °C (930 °F), the compound mixture decomposes to form a mixture of silver and cadmium oxide. Alkali-metal content can be controlled in the ppm range by adequate washing. Controlled amounts of sodium, potassium, and lithium may enhance electrical life. Excessive amounts of these elements can lead to rapid erosion, restrike, and generally poor electrical life. Depending on device design, the range can be from 10 to 300 ppm. Contacts are consolidated from this mixture by conventional P/M methods. The microstructure of contacts made by this method displays a finer particle size and a more uniformly dispersed CdO phase than material made by conventional blending.

Selected References

- Y-S. Shen et al., Electrical Contact Materials, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 840-868

Thermocouple Materials

Introduction

THE THERMOCOUPLE THERMOMETER is by far the most widely used device for measurement of temperature used in the metals industry. It is estimated that well over 90% of the temperature sensing devices used in this industry are thermocouple thermometers. Favorable characteristics of these devices include good accuracy, suitability over a wide temperature range, fast thermal response, ruggedness, high reliability, low cost, and great versatility of application.

Essentially, a thermocouple thermometer is a system consisting of a temperature-sensing element called a thermocouple, which produces an electromotive force (emf) that varies with temperature, a device for measuring emf, which may include a printed scale for converting emf to equivalent temperature units and an electrical conductor (extension wires) for connecting the thermocouple to the emf measurement device. The principles on which thermocouples depend, as well as their design considerations are described in detail in the article "Thermocouple Materials," in Volume 2 of *ASM Handbook.*

Thermocouple Principles

A thermocouple is a device in which the temperature difference between the ends of a pair of dissimilar metal wires is deduced from a measurement of the difference in the thermo-electric potentials developed alone the wires. The presence of a temperature gradient in a metal or alloy leads to an electric potential gradient being set up along the temperature gradient. This thermoelectric potential gradient is proportional to the temperature gradient and varies from metal to metal. It is the fact that the thermoelectric emf is different in different metals and alloys for the same temperature gradient that allows the effect to be used for the measurement of temperature.

The basic circuit of a thermocouple is shown in Fig. 1(a). Thermocouples consist of two dissimilar wires joined (brazed or welded) at one end, forming a measuring, or hot, junction. The other end, which is connected to the copper wire of the measuring circuitry, is called the reference, or cold, junction. The electrical signal output in millivolts is proportional to the difference in temperature between the measuring (hot) junction and the reference (cold) junction. The different types of thermocouples, classified by their metallurgical compositions, have differing output signal calibrations.

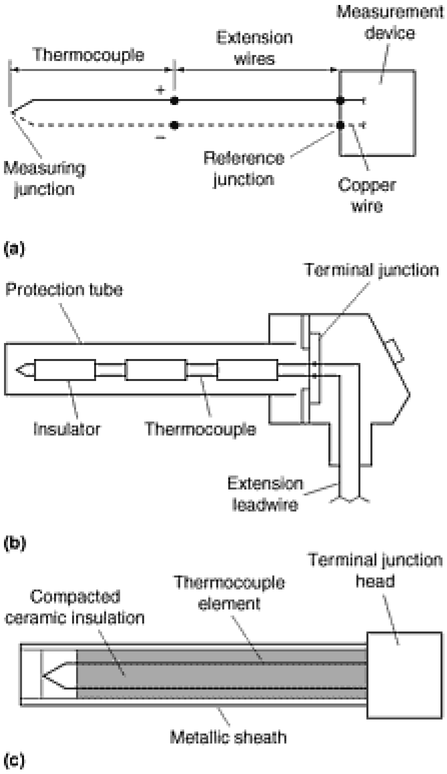

Fig. 1 Schematics showing (a) the basic thermocouple circuit (the positive and negative symbols represent the positive and negative thermoelements with reference to Platinum 67), (b) conventional thermocouple assembly, and (c) compacted ceramic thermocouple assembly

The thermocouple wire combination is called a thermocouple element. A complete thermocouple assembly includes the element and a system for electrically insulating the wires and protecting them form the operating environment (see the subsection "Insulation and Protection"). In addition, the assembly provides mounting fittings and a terminal junction in a head assembly. Extension lead wires, which match the thermoelectric characteristics of the thermocouple elements, are used to connect these terminal junctions to the instrumentation. Figure 1(b) shows a complete thermocouple assembly in a protection tube. The operating life and accuracy of a thermocouple depend on operating temperature, time at operating temperature, and number of high-to-low temperature cycles.

Types of Thermocouples

Commercially available thermocouples are grouped according to material characteristics (base metal or noble metal) and standardization. At present, five base-metal thermocouples and three noble-metal thermocouples have been standardized and given letter designations by ANSI (American National Standards Institute), ASTM (American Society for Testing and Materials), and ISA (Instrument Society of America). Among the remaining thermocouples in use, some have not been assigned letter designations because of limited usage, and some are being considered for standardization.

Standard Thermocouples

Table 1 presents base compositions, melting points, and electrical resistivites of the individual thermoelements of the seven standard thermocouples. Maximum operating temperatures and limiting factors in environmental conditions are listed also.

Table 1 Properties of standard thermocouples

Type	Thermoelements	Base composition	Melting point, °C	Resisivity nΩ · m	Recommended service	Maximum temperature	
						°C	**°F**
J	JP	Fe	1450	100	Oxidizing or reducing	760	1400
	JN	44Ni-55Cu	1210	500			
K	KP	90Ni-9Cr	1350	700	Oxidizing	1260	2300
	KN	94Ni-Al, Mn, Fe, Si, Co	1400	320			
N	NP	84Ni-14Cr-1.4Si	1410	930	Oxidizing	1260	2300
	NN	95Ni-4.4Si-0.15Mg	1400	370			
T	TP	OFHC Cu	1083	17	Oxidizing or reducing	370	700
	TN	44Ni-55Cu	1210	500			
E	EP	90Ni-9Cr	1350	700	Oxidizing	870	1600
	EN	44Ni-55Cu	1210	500			
R	RP	87Pt-13Rh	1860	196	Oxidizing or inert	1480	2700
	RN	Pt	1769	104			
S	SP	90Pt-10Rh	1850	189	Oxidizing or inert	1480	2700
	SN	Pt	1769	104			
B	BP	70Pt-30Rh	1927	190	Oxidizing, vacuum or inert	1700	3100

The type J thermocouple is widely used, primarily because of its versatility and low cost. In this couple, the positive thermoelement is iron (containing small amounts of carbon, cobalt, manganese, and silicon), and the negative thermoelement is constantan, a 44Ni-55Cu alloy. Type J couples can be used in both oxidizing and reducing atmospheres at temperatures up to approximately 760 °C (1400 °F). They find extensive use in heat-treating applications in which they are exposed directly to the furnace atmosphere.

Type K thermocouples, like type J couples, are also widely used in industrial applications. The positive thermoelement is a 90Ni-9Cr alloy; the negative thermoelement is a 94% Ni alloy containing silicon, manganese, aluminum, iron, and cobalt as alloying constituents. Type K thermocouples can be used at temperatures up to 1250 °C (2280 °F) in oxidizing atmospheres.

Type K couples should not be used in elevated-temperature service in reducing atmospheres or in environments containing sulfur, hydrogen or carbon monoxide. At elevated temperatures in oxidizing atmospheres, uniform oxidation occurs, and the oxide formed on the surface of the positive (90Ni-10Cr) thermoelement is a spinel, NiO-Cr_2O_3. However, in reducing atmospheres, preferential oxidation of chromium occurs forming only Cr_2O_3. The presence of this greenish oxide (commonly known as "green rot") depletes the chromium content, causing a very large negative shift of the thermal emf and rapid deterioration of the thermoelement.

Type N. The Nicrosil/Nisil thermocouple (type N in Table 1) was developed for oxidation resistance and emf stability superior to those of type K thermocouples at elevated temperatures. The positive thermoelement is Nicrosil (nominal composition 14 Cr, 1.3 Si, 0.1 Mg, bal Ni), and the negative thermoelement is Nisil (nominal composition 4.4 Si, 0.1 Mg, bal Ni). These couples have been shown to have longer life and better emf stability than type K thermocouples at elevated temperatures in air, both in the laboratory and in several industrial applications.

Type T thermocouples are used extensively for cryogenic measurements. The positive thermoelement is oxygen-free high conductivity (OFHC) copper (C10100). The constantan (44Ni-55Cu) used for the negative thermoelement of the type T couple has the same base composition as that of the constantan used in the type J couple, but is slightly different in minor alloying constituents. Type T couples can be used in either oxidizing or reducing atmospheres. They should not be used above 370 °C (700 °F) because of the poor oxidation resistance of copper.

Type E. The positive thermoelement of the type E thermoelement is 90Ni-9Cr, the same as that of the type K thermocouple; the negative element is 44Ni-55Cu, the same as that of the type T couple. The recommended maximum operating temperature for type E thermocouples is 870 °C (1600 °F). Like type K thermocouples, the type E couples should be used only in oxidizing atmospheres because their use in reducing atmospheres results in preferential oxidation of chromium (green rot).

The type S thermocouple served as the interpolating instrument for defining the International Practical Temperature Scale of 1968 (amended in 1975) from the freezing point of antimony (630.74 °C, or 1167.33 °F) to the freezing point of gold (1064.43 °C, or 1947.97 °F). It is characterized by a high degree of chemical inertness and stability at high temperatures in oxidizing atmospheres. The materials used in the legs of this thermocouple, Pt-10Rh and platinum, both are ductile and can be drawn into fine wire (as small as 0.025 mm, or 0.001 in., in diameter for special applications).

The type S couple is widely used in industrial laboratories as a standard for calibration of base-metal thermocouples and other temperature-sensing instruments. It is commonly used for controlling processing of steel, glass, and many refractory materials. It should be used in air or in oxidizing or inert atmospheres. It should not be used unprotected in reducing atmospheres in the presence of easily reduced oxides, atmospheres containing metallic vapors such as lead or zinc, or atmospheres containing nonmetallic vapors such as arsenic, phosphorus, or sulfur. It should not be inserted directly into metallic protection tubes and is not recommended for service in vacuum at high temperatures except for short periods of time. Because the negative leg of this couple is fabricated from high-purity platinum (approximately 99.99% for commercial couples and 99.995%+ for special grades), special care should be taken to protect the couple from contamination by the insulators used as well as by the operating environment.

The type R thermocouple (Pt-13Rh/Pt) has characteristics and end-use applications similar to those of the type S couple.

Type B thermocouples (Pt-30Rh/Pt-6Rh) can be used in still air or inert atmospheres for extended periods at temperatures up to 1700 °C (3100 °F) and intermittently up to 1760 °C (3200 °F) (Pt-6Rh leg melts at approximately 1826 °C, or 3319 °F). Because both of its legs are platinum-rhodium alloys, the type B couple is less sensitive than type R or type S to pickup of trace impurities from insulators or from the operating environment. Under corresponding conditions of temperature and environment, type B thermocouples exhibit less grain growth and less drift in calibration than type R or type S thermocouples.

The type B couple also is suitable for short-term use in vacuum at temperatures up to approximately 1700 °C (3100 °F). It should not be used in reducing atmospheres, or in those containing meatallic or nonmetallic vapors, unless suitably protected with ceramic protection tubes. It should never be inserted directly into a metallic primary protection tube.

Nonstandard Thermocouples

The 19 alloy/20 alloy thermocouple was developed for temperature-sensing and control applications at elevated temperatures in hydrogen or in reducing atmospheres. The positive thermoelement is the 20 alloy, which has a nominal composition of 82Ni-18Mo. The negative thermoelement is the 19 alloy, the nominal composition of which is 99Ni-1Co.

19 alloy/20 alloy thermocouples can be used in hydrogen or in reducing atmospheres over the entire range from 0 to 1260 °C (32 to 2300 °F) with excellent performance. The oxidation resistance of 19 alloy/20 alloy is not good when compared with that of the standard type K couple. 19 alloy/20 alloy thermocouples should not be used in oxidizing atmospheres above 650 °C (1200 °F).

Iridium-Rhodium. Three iridium-rhodium thermocouples are commercially available: 60Ir-40Rh/Ir (the most widely used), 50Ir-50Rh/Ir, and 40Ir-60Rh/Ir. Iridium-rhodium couples are suitable for use for limited periods of time in air or other oxygen-carrying atmospheres at temperatures up to approximately 2000 °C (3600 °F) and generally are used for such service at temperatures above the range in which types R, S, and B thermocouples are employed. They can be used in inert atmospheres and in vacuum, but not in reducing atmospheres.

Platinum-Molybdenum. The Pt-5Mo/Pt-0.1Mo thermocouple is used for measuring temperatures from 1100 to approximately 1500 °C (2000 to approximately 2700 °F) under neutron radiation (type K couples are employed for temperatures up to 1100 °C).

Platinel thermocouples are an all-noble-metal combination. Actually, two combinations have been produced: Platinel I and Platinel II. Both have negative legs of 65Au-35Pd. The positive leg of the Platinel I couple is 83Pd-14Pt-3Au, and the positive leg of the Platinel II couple consists of 55PD-3/Pt-14Au. Platinel couples can be used unprotected (insulators only) in air to 1200 °C (2190 °F) for extended periods of time and to 1300 °C (2370 °F) for shorter periods.

Tungsten-Rhenium. Three tungsten-rhenium thermocouples are commercially available: W/W-26Re, doped W-3Re/W-25Re, and W-5Re/W-26Re. All three couples have been used at temperatures up to 2760 °C (5000 °F), but they usually are employed below 2315 °C (4200 °F). These thermocouples are limited to operation in reducing atmospheres, high vacuum, and inert gases due to their tendency toward oxidation.

Insulation and Protection

To operate properly, thermocouple wires must be electrically insulated from one another at all points other than the measuring junction and must be protected from the operating environment.

In conventional thermocouple assemblies, insulated thermocouple wires are enclosed in protection tubes. For cryogenic application (below 0 °C, and as low as approximately 4 K) varnish or varnish-type coatings are used to insulate thermoelements from one another. At higher temperatures (up to approximately 300 °C), insulating materials include polyvinyl chloride, thermoplastic elastomer, nylon, teflon, and polyimide. At temperatures above 300 °C (570 °F), hard-fired ceramics are used. For base-metal thermocouples, mullite, alumina, and steatite are used. Depending on the temperature and the environment, noble-metal or nonstandard thermocouples can be insulated with quartz, mullite, sillimanite, porcelain, alumina, beryllia, thoria, or hafnia.

Insulated thermocouple elements are used inside protection tubes or wells, which provide mechanical support and protect the thermocouple from the process environment. Protection tubes are made from metal (carbon steel, chromium-molybdenum alloy steels, stainless steels, and nickel alloys) or ceramic materials (porcelain, alumina, or silicon carbide). Wells, which are used to protect thermocouples in liquid or gaseous environments at pressures greater than 345 kPa (50 psi), are metallic.

Compacted ceramic thermocouples use a ceramic powder to insulate the thermocouple wires (Fig. 1c). These wires are compacted inside a metal sheath, providing protection from environment. Sheaths, which are selected to suit specific end-use requirements include 300 series austenitic stainless steels, nickel-base alloys (Hastelloy X and Inconel 600 and 702), and tantalum and niobium alloys. Depending on temperature and application, magnesia, alumina, beryllia, or thoria can be used for the insulation.

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- T.P. Wang, Thermocouple Materials, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 869-888

Low-Expansion Alloys

Introduction

LOW-EXPANSION ALLOYS are materials with dimensions that do not change appreciably with temperature. Alloys included in this category are various binary iron-nickel alloys and several ternary alloys of iron combined with nickel-chromium, nickel-cobalt, or cobalt-chromium alloying. Low-expansion alloys are used in applications such as rods and tapes for geodetic surveying, compensating pendulums and balance wheels for clocks and watches, moving parts that require control of expansion (such as pistons for some internal-combustion engines), bimetal strip, glass-to-metal seals, thermostatic strip, vessels and piping for storage and transportation of liquefied natural gas, superconducting systems in power transmissions, integrated-circuit lead frames, components for radios and other electronic devices, and structural components in optical and laser measuring systems.

Iron-Nickel Alloys

Alloys of iron and nickel have coefficients of linear expansion ranging from a small negative value (-0.5 ppm/°C) to a large positive (20 ppm/°C) value. Figure 1 shows the effect of nickel content on the linear expansion of iron-nickel alloys at room temperature. In the range of 30 to 60% Ni, it is possible to select alloys with appropriate expansion characteristics. The alloy containing 36% Ni (with small quantities of manganese, silicon, and carbon amounting to a total of less than 1%) has a coefficient of expansion so low that its length is almost invariable for ordinary changes in temperature. This alloy is known as Invar, which is a trade name meaning invariable.

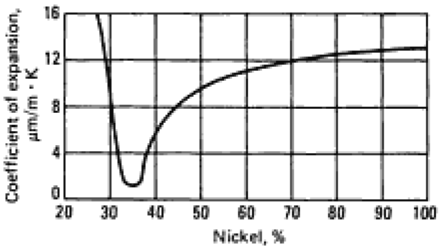

Fig. 1 Coefficient of linear expansion at 20 °C versus nickel content for iron-nickel alloys containing 0.4% Mn and 0.1% C

After the discovery of Invar, an intensive study was made of the thermal and elastic properties of several similar alloys. Iron-nickel alloys that have nickel contents higher than that of Invar retain to some extent the expansion characteristics of Invar. Alloys that contain less than 36% Ni have much higher coefficients of expansion than alloys containing 36% or more Ni.

Invar

Invar (UNS number K93601) and related alloys have low coefficients of expansion over only a rather narrow range of temperature (see Fig. 2). At low temperatures in the region from A to B, the coefficient of expansion is high. In the interval between B and C, the coefficient decreases, reaching a minimum in the region from C to D. With increasing temperature, the coefficient begins again to increase from D to E, and thereafter (from E to F), the expansion curve follows a trend similar to that of the nickel or iron of which the alloy is composed. The minimum expansivity prevails only in the range from C to D.

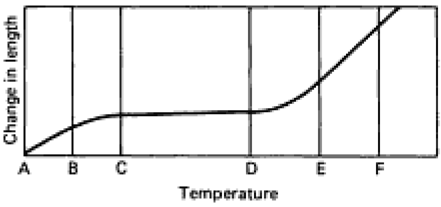

Fig. 2 Change in length of a typical Invar alloy over different ranges of temperature

In the region between D and E in Fig. 2, the coefficient is changing rapidly to a higher value. The temperature limits for a well-annealed 36% Ni iron are 162 and 271 °C (324 and 520 °F). These temperatures correspond to the initial and final losses of magnetism in the material (that is, the Curie temperature). The slope of the curve between C and D is then a measure of the coefficient of expansion over a limited range of temperature.

Table 1 gives coefficients of linear expansion of iron-nickel alloys between 0 and 38 °C (32 and 100 °F). The expansion behavior of several iron-nickel alloys over wider ranges of temperature is represented by curves 1 to 5 in Fig. 3. For comparison, Fig. 3 also includes the similar expansion obtained for ordinary steel.

Table 1 Thermal expansion of iron-nickel alloys between 0 and 38 °C

Ni, %	Mean coefficient, μm/m · K
31.4	3.395 + 0.00885 *t*
34.6	1.373 + 0.00237 *t*
35.6	0.877 + 0.00127 *t*
37.3	3.457 - 0.00647 *t*
39.4	5.357 - 0.00448 *t*
43.6	7.992 - 0.00273 *t*
44.4	8.508 - 0.00251 *t*
48.7	9.901 - 0.00067 *t*
50.7	9.984 + 0.00243 *t*
53.2	10.045 + 0.00031 *t*

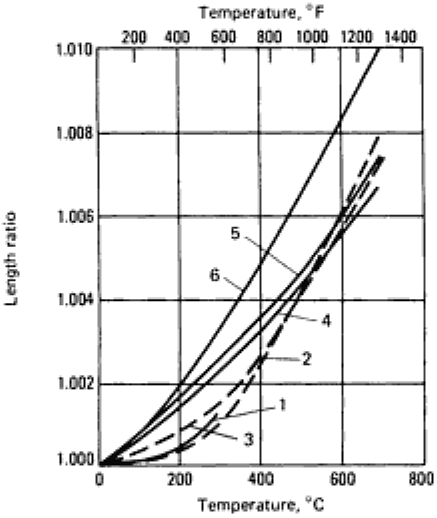

Fig. 3 Thermal expansion of iron-nickel alloys. Curve 1, 64Fe-31Ni-5Co; curve 2, 64Fe-36Ni (Invar); curve 3, 58Fe-42Ni; curve 4, 53Fe-47Ni; curve 5, 48Fe-52Ni; curve 6, carbon steel (0.25% C)

Effects of Composition on Expansion Coefficient. Figure 1 shows the effect of variation in nickel content on linear expansivity. Minimum expansivity occurs at approximately 36% Ni, and small additions of other metals have considerable influences on the position of this minimum. Because further additions of nickel raise the temperature at which the inherent magnetism of the alloy disappears, the inflection temperature in the expansion curve (Fig. 2) also rises with increasing nickel content.

The addition of third and fourth elements to iron-nickel provides useful changes of desired properties (mechanical and physical), but significantly changes thermal expansion characteristics. Minimum expansivity shifts toward higher nickel contents when manganese or chromium is added, and toward lower nickel contents when copper, cobalt, or carbon is added. Except for the ternary alloys with Ni-Fe-Co compositions (Super Invars), the value of the minimum expansivity for any of these ternary alloys is, in general, greater than that of a typical Invar alloy.

Figure 4 shows the effects of additions of manganese, chromium, copper, and carbon. Additions of silicon, tungsten, and molybdenum produce effects similar to those caused by additions of manganese and chromium; the composition of minimum expansivity shifts toward higher contents of nickel. Addition of carbon is said to produce instability in Invar, which is attributed to the changing solubility of carbon in the austenitic matrix during heat treatment.

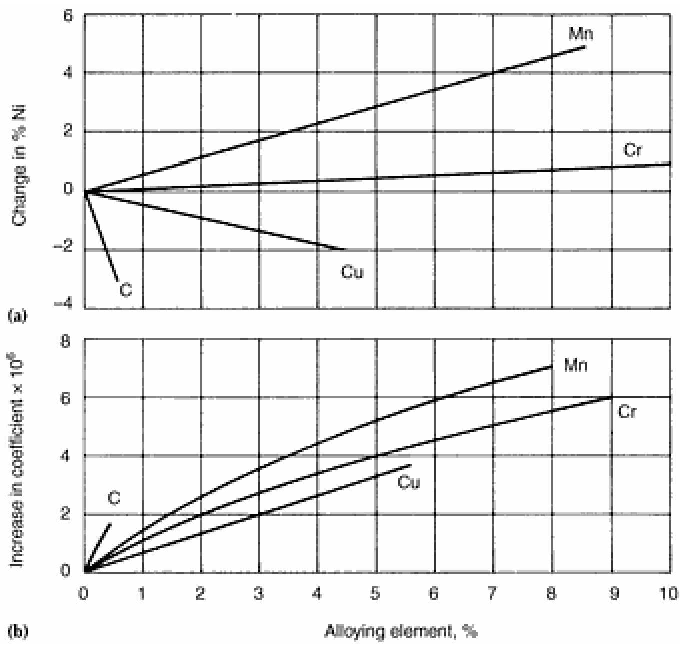

Fig. 4 Effect of alloying elements on expansion characteristics of iron-nickel alloys. (a) Displacement of nickel content caused by additions of manganese, chromium, copper, and carbon to alloy of minimum expansivity. (b) Change in value of minimum coefficient of expansion caused by additions of manganese, chromium, copper, and carbon

Effects of Processing. Heat treatment and cold work change the expansivity of Invar alloys considerably. Table 2 shows the effect of heat treatment for a 36% Ni Invar alloy. The expansivity is greatest in well-annealed material and least in quenched material.

Table 2 Effect of heat treatment on coefficient of thermal expansion of Invar

Condition	Mean coefficient, μm/m · K
As forged	
At 17-100 °C (63-212 °F)	1.66
At 17-250 °C (63-480 °F)	3.11
Quenched from 830 °C (1530 °F)	
At 18-100 °C (65-212 °F)	0.64
At 18-250 °C (65-480 °F)	2.53
Quenched from 830 °C and tempered	
At 16-100 °C (60-212 °F)	1.02
At 16-250 °C (60-480 °F)	2.43
Quenched from 830 °C to room temperature in 19 h	
At 16-100 °C (60-212 °F)	2.01
At 16-250 °C (60-480 °F)	2.89

Annealing is done at 750 to 850 °C (1380 to 1560 °F). When the alloy is quenched in water from these temperatures, expansivity is decreased, but instability is induced both in actual length and in coefficient of expansion. To overcome these deficiencies and to stabilize the material, it is common practice to stress relieve at approximately 315 to 425 °C (600 to 800 °F) and to age at a low temperature 90 °C (200 °F) for 24 to 48 hours.

Cold drawing also decreases the thermal expansion coefficient of Invar alloys. The values for the coefficients in the following table are from experiments on two heats of Invar:

Material condition	Expansivity, ppm/°C
Direct from hot mill	1.4 (heat 1)
	1.4 (heat 2)
Annealed and quenched	0.5 (heat 1)
	0.8 (heat 2)
Quenched and cold drawn (>70% reduction with a diameter of 3.2 to 6.4 mm, or 0.125 to 0.250 in.)	0.14 (heat 1)

By cold working after quenching, it is possible to produce material with a zero, or even a negative, coefficient of expansion. A negative coefficient can be increased to zero by careful annealing at a low temperature. However, these artificial methods of securing an exceptionally low coefficient can produce instability in the material. With lapse of time and variation in temperature, exceptionally low coefficients usually revert to normal values. For special applications (geodetic tapes, for example), it is essential to stabilize the material by cooling it slowly from 100 to 20 °C (212 to 68 °F) over a period of many months, followed by prolonged aging at room temperature. However, unless the material is to be used within the limits of normal atmospheric variation in temperature, such stabilization is of no value. Although these variations in heat-treating practice are important in special applications, they are of little significance for ordinary uses.

Magnetic Properties. Invar and all similar iron-nickel alloys are ferromagnetic at room temperature and become paramagnetic at higher temperatures. Because additions in nickel contents raise the temperature at which the inherent magnetism of the alloy disappears, the inflection temperature in the expansion curve rises with increasing nickel content. The loss of magnetism in a well-annealed sample of a true Invar begins at 162 °C (324 °F) and ends at 271 °C (520 °F). In a quenched sample, the loss begins at 205 °C (400 °F) and ends at 271 °C (520 °F).

Electrical Properties. The electrical resistance of 36Ni-Fe Invar is between 750 and 850 nΩ · m at ordinary temperatures. The temperature coefficient of electrical resistivity is about 1.2 mΩ/Ω · K over the range of low expansivity. As nickel content increases above 36%, the electrical resistivity decreases to approximately 165 nΩ · m at approximately 80% NiFe.

Other Physical and Mechanical Properties. Table 3 presents data on miscellaneous properties of Invar in the hot-rolled and forged conditions. Figure 5 illustrates the effects of temperature on mechanical properties of forged 66Fe-34Ni.

Table 3 Physical and mechanical properties of Invar

Solidus temperature, °C (°F)	**1425 (2600)**
Density, g/cm^3	8.1
Tensile strength, MPa (ksi)	450-585 (65-85)
Yield strength, MPa (ksi)	275-415 (40-60)
Elastic limit, MPa (ksi)	140-205 (20-30)
Elongation, %	30-45
Reduction in area, %	55-70
Scleroscope hardness	19
Brinell hardness	160
Modulus of elasticity, GPa (10^6 psi)	150 (21.4)
Thermoelastic coefficient, μm/m · K	500
Specific heat, at 25-100 °C (78-212 °F), J/kg · °C (Btu/lb · °F)	515 (0.123)
Thermal conductivity, at 20-100 °C (68-212 °F), W/m · K (Btu/lb · h · °F)	11 (6.4)
Thermoelectric potential (against copper), at -96 °C (-140 °F), μV/K	9.8

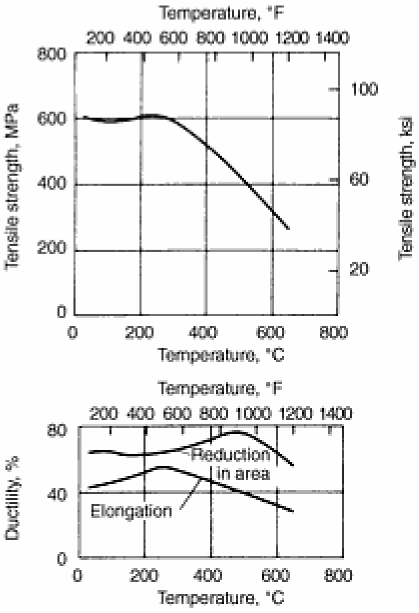

Fig. 5 Mechanical properties of a forged 34% Ni alloy. Alloy composition: 0.25 C, 0.55 Mn, 0.27 Si, 33.9 Ni, bal Fe. Heat treatment: annealed at 800 °C (1475 °F) and furnace cooled.

Iron-Nickel Alloys Other Than Invar

Iron-nickel alloys that have nickel contents higher than that of Invar retain to some extent the expansion characteristics of Invar. Because further additions of nickel raise the temperature at which the inherent magnetism of the alloy disappears, the inflection temperature in the expansion curve rises with increasing nickel content. Although this increase in range is an advantage in some circumstances, it is accompanied by an increase in coefficient of expansion. Table 4 and Fig. 6 present information on the coefficients of expansion of iron-nickel alloys at temperatures up to the inflection temperature. They also give data on alloys containing up to 68% Ni. Of significant commercial interest are those alloys containing approximately 40 to 50% Ni such as thermostat alloys 42% Ni iron (UNS K94200) and 45% Ni iron (UNS K94500) and glass sealing alloys such as Dumet (UNS 94101), 51% Ni iron, and 52% Ni iron.

Table 4 Expansion characteristics of iron-nickel

Composition, %			Inflection temperature		Mean coefficient of expansion, from 20 °C to inflection temperature, μm/m · K
Mn	**Si**	**Ni**	**°C**	**°F**	
0.11	0.02	30.14	155	310	9.2
0.15	0.33	35.65	215	420	1.54
0.12	0.07	38.70	340	645	2.50
0.24	0.03	41.88	375	710	4.85
. . .	. . .	42.31	380	715	5.07
. . .	. . .	43.01	410	770	5.71
. . .	. . .	45.16	425	800	7.25
0.35	. . .	45.22	425	800	6.75
0.24	0.11	46.00	465	870	7.61
. . .	. . .	47.37	465	870	8.04
0.09	0.03	48.10	497	925	8.79
0.75	0.00	49.90	500	930	8.84
. . .	. . .	50.00	515	960	9.18
0.25	0.20	50.05	527	980	9.46
0.01	0.18	51.70	545	1015	9.61
0.03	0.16	52.10	550	1020	10.28

0.35	0.04	52.25	550	1020	10.09
0.05	0.03	53.40	580	1075	10.63
0.12	0.07	55.20	590	1095	11.36
0.25	0.05	57.81	. . .	. . .	12.24
0.22	0.07	60.60	. . .	. . .	12.78
0.18	0.04	64.87	. . .	. . .	13.62
0.00	0.05	67.98	. . .	. . .	14.37

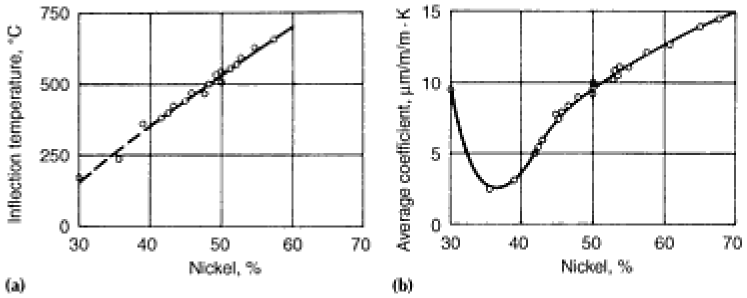

Fig. 6 Effect of nickel content on expansion of iron-nickel alloys. (a) Variation of inflection temperature. (b) Variation of average coefficient of expansion between room temperature and inflection temperature

Special Alloys

Fe-Ni-Cr Alloys. Elinvar is a 52Fe-36Ni-12Cr alloy with a zero thermoelastic coefficient (that is, an invariable modulus of elasticity over a wide temperature range). It is used for such articles as hair springs and balance wheels for clocks and watches and for tuning forks used in radio synchronization. Other Fe-Ni-Cr alloys with 40 to 48% Ni and 2 to 8% Cr are useful as glass-sealing alloys.

Fe-Ni-Co Alloys. Replacement of some of the nickel by cobalt in an alloy of the Invar composition lowers the thermal expansion coefficient and makes the alloy's expansion characteristics less susceptible to variations in heat treatment. One such alloy is the Super Invar with a nominal 32% Ni and 4 to 5% Co. Its expansion coefficient is lower than that of Invar, but over a narrower temperature range.

Kovar (UNS 94610) is a nominal 29%Ni-17%Co-54%Fe alloy that is a well-known glass-sealing alloy suitable for sealing to a hard (borosilicate) glasses. Kovar has a nominal expansion coefficient of approximately 5 ppm/°C and inflection temperature of approximately 450 °C (840 °F).

Fe-Co-Cr Alloys. An alloy containing 36.5 to 37% Fe, 53 to 54.5% Co. and 9 to 10% Cr has an exceedingly low, and at times, negative (over the range from 0 to 100 °C, or 32 to 212 °F) coefficient of expansion. This alloy has good corrosion resistance compared to low-expansion alloys without chromium. Consequently, it has been referred to as "Stainless Invar."

High-Strength, Controlled-Expansion Alloys. There is a family of Fe-Ni-Co alloys strengthened by the addition of niobium and titanium that show the strength of precipitation-hardened superalloys while maintaining low coefficients of thermal expansion typical of certain alloys from the Fe-Ni-Co system. Table 5 shows compositions and properties of these alloys. The combination of exceptional strength and low coefficient of expansion makes this family useful for applications requiring close operating tolerances over a range of temperatures. Several components for gas turbine engines are produced from these alloys.

Table 5 Compositions, thermal expansion coefficients, and room-temperature tensile properties of high-strength controlled-expansion alloys

Alloy designation	UNS No.	Composition, %	Coefficient of thermal expansion, from room temperature to:						Inflection temperature		Ultimate tensile strength		0.2% yield strength		Elongation, %	Reduction in area %
			260 °C	**(500 °F)**	**370 °C**	**(700 °F)**	**415 °C**	**(780 °F)**								
			ppm/°C	**ppm/°F**	**ppm/°C**	**ppm/°F**	**ppm/°C**	**ppm/°F**	**°C**	**°F**	**MPa**	**ksi**	**MPa**	**ksi**		
Incoloy 903 and Pyromet CTX-1	N19903	0.03 C, 0.20 Si, 37.7 Ni, 16.0 Co, 1.75 Ti, 3.0 (Nb + Ta), 1.0 Al, 0.0075 B, bal Fe	7.51	4.17	7.47	4.15	7.45	4.14	440	820	1480	215	1310	190	15	45
Incoloy 907 and Pyromet CTX-3	N19907	0.06 C max, 0.5 Si, 38.0 Ni, 13.0 Co, 1.5 Ti, 4.8 (Nb + Ta), 0.35 Al max, 0.012 B max, bal Fe	7.65	4.25	7.50	4.15	7.55	4.20	415	780	1170	170	825	120	15	25
Incoloy 909 and Pyromet CTX-909	N199009	0.06 C max, 0.40 Si, 38.0 Ni, 14.0 Co, 1.6 Ti, 4.9 (Nb + Ta), 0.15 Al max, 0.012 B max, bal Fe	7.75	4.30	7.55	4.20	7.75	4.30	415	780	1310	190	1070	155	10	20

Selected References

- E.L. Frantz, Low-Expansion Alloys, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 889-896
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Shape Memory Alloys

Introduction

THE TERM SHAPE MEMORY ALLOYS (SMA) is applied to that group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure. Generally, these materials can be plastically deformed at some relatively low temperature, and upon exposure to some higher temperature will return to their shape prior to the deformation. Materials that exhibit shape memory only upon heating are referred to as having a one-way shape memory. Some materials also undergo a change in shape upon recooling. These materials have a two-way shape memory.

Although a relatively wide variety of alloys are known to exhibit the shape memory effect, only those that can recover substantial amounts of strain or that generate significant force upon changing shape are of commercial interest. To date this has been the NiTi alloys and copper-base alloys such as Cu-Zn-Al and Cu-Al-Ni.

A shape memory alloy is further defined as an alloy that yields a thermoelastic martensite. In this case, the alloy undergoes a martensitic transformation of a type that allows the alloy to be deformed by a twinning mechanism below the transformation temperature. The deformation is then reversed when the twinned structure reverts upon heating to the parent phase.

General Characteristics

The martensitic transformation that occurs in the shape memory alloys yields a thermoelastic martensite and develops from a high-temperature austenite phase with long-range order. The martensite typically occurs as alternately sheared platelets, which are seen as a herringbone structure when viewed metallographically (Fig. 1b). The transformation, although a first-order phase change, does not occur at a single temperature but over a range of temperatures that varies with each alloy system. The typical method of characterizing the transformation and naming each point in the cycle is shown in Fig. 1(a). Most of the transformation occurs over a relatively narrow temperature range, although the beginning and end of the transformation during heating or cooling actually extends over a much larger temperature range. The transformation also exhibits hysteresis in that the transformation on heating and on cooling does not overlap (Fig. 1a). This transformation hysteresis (shown as T in Fig. 1a) varies with the alloy system.

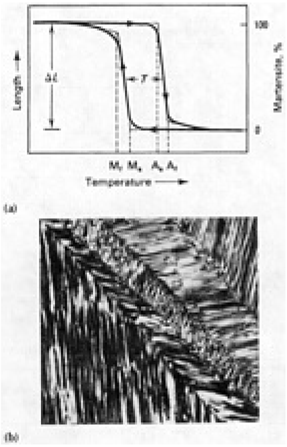

Fig. 1 Characteristics of shape memory alloys. (a) Typical transformation versus temperature curve for a specimen under constant load (stress) as it is cooled and heated. *T,* transformation hysteresis. M_s, martensite start; M_f, martensite finish; A_s, austenite start; A_f, austenite finish. (b) Martensitic structure typical of those in copper-aluminum, copper-tin, and copper-zinc alloys.

Commercial SMA Alloys

Properties of NiTi and Cu-base SMA alloys are quite different. The NiTi alloys have greater shape memory strain (up to 8% versus 4 to 5% for the copper-base alloys), tend to be much more thermally stable, have excellent corrosion resistance compared to the medium corrosion resistance and susceptibility to stress-corrosion cracking of the copper-base alloys, and have much higher ductility. Conversely, the copper-base alloys are much less expensive, can be melted and extruded in air with ease, and have a wider range of potential transformation temperatures. The two alloy systems thus have advantages and disadvantages that must be considered in a particular application.

Nickel-Titanium Alloys

The basis of the nickel-titanium system of alloys is the binary, equiatomic (49 to 51 at.% Ni) intermetallic compound of NiTi. This intermetallic compound is extraordinary because it has a moderate solubility range for excess nickel or titanium, as well as most other metallic elements, and it also exhibits a ductility comparable to most ordinary alloys. This solubility allows alloying with many of the elements to modify both the mechanical properties and the transformation properties of the system. Excess nickel, in amounts up to approximately 1%, is the most common alloying addition. Excess nickel strongly depresses the transformation temperature and increases the yield strength of the austenite. Other frequently used elements are iron and chromium (to lower the transformation temperature), and copper (to decrease the hysteresis and lower the deformation stress of the martensite). Because common contaminants such as oxygen and carbon can also shift the transformation temperature and degrade the mechanical properties, it is also desirable to minimize the amount of these elements.

Properties. Table 1 shows the major physical properties of the basic binary Ni-Ti system and some of the mechanical properties of the alloy in the annealed condition. Note that this is for the equiatomic alloy with an A_f value of approximately 110 °C (230 °F). Selective work hardening, which can exceed 50% reduction in some cases, and proper heat treatment can greatly improve the ease with which the martensite is deformed, give an austenite with much greater strength, and create material that spontaneously moves itself both on heating and on cooling (two-way shape memory). One of the biggest challenges in using this family of alloys is in developing the proper processing procedures to yield the properties desired.

Table 1 Properties of binary nickel-titanium shape memory alloys

Properties	Property value
Melting temperatures, °C (°F)	1300 (2370)
Density, g/cm^3 ($lb/in.^3$)	6.45 (0.233)

Resistivity, $\mu\Omega \cdot$ cm	
Austenite	∼100
Martensite	∼70
Thermal conductivity, W/m · °C (Btu/ft · h · °F)	
Austenite	18 (10)
Martensite	8.5 (4.9)
Corrosion resistance	Similar to 300 series stainless steel or titanium alloys
Young's modulus, GPa (10^6 psi)	
Austenite	∼83 (∼12)
Martensite	∼28-41 (∼4-6)
Yield strength, MPa (ksi)	
Austenite	195-690 (28-100)
Martensite	70-140 (10-20)
Ultimate tensile strength, MPa (ksi)	895 (130)
Transformation temperatures, °C (°F)	-200 to 110 (-325 to 230)
Hysteresis, Δ°C (Δ°F)	∼30 (∼55)
Latent heat of transformation, kJ/kg · atom (cal/g · atom)	167 (40)
Shape memory strain	8.5% maximum

Processing. Because of the reactivity of the titanium in these alloys, all melting of them must be done in a vacuum or an inert atmosphere. Methods such as plasma-arc melting, electron-beam melting, and vacuum-induction melting are all used commercially. After ingots are melted, standard hot-forming processes such as forging, bar rolling, and extrusion can be used for initial breakdown. The alloys react slowly with air, so hot working in air is quite successful. Most cold-working processes can also be applied to these alloys, but they work harden extremely rapidly, and frequent annealing is required. Wire drawing is probably the most widely used of the techniques, and excellent surface properties and sizes as small as 0.05 mm (0.002 in.) are made routinely.

Heat treating to impart the desired memory shape is often done at 500 to 800 °C (950 to 1450 °F), but it can be done as low as 300 to 350 °C (600 to 650 °F) if sufficient time is allowed. The SMA component may need to be restrained in the desired memory shape during the heat treatment; otherwise, it may not remain there.

Applications for NiTi alloys can be grouped into four broad categories: actuation devices, constrained recovery devices, superelastic devices, and martensitic devices.

Shape memory actuation devices utilize the shape memory effect to recover a particular shape upon heating above their transformation temperatures. Shape memory actuation devices can act without constraint to freely recover their trained shape, can be fully constrained so that they provide a force, or can be partially constrained so that they perform work. The transformation temperatures of the NiTi alloy can be adjusted to activate at precisely the required temperature. Common actuation temperatures are human body temperature and boiling water temperature. Examples of shape memory actuation devices include blood-cot filters (NiTi wire is shaped to anchor itself in a vein and catch passing clots), vascular stents to reinforce blood vessels, and coffeepot thermostats.

The most successful example of constrained recovery devices is hydraulic pipe couplings. These fittings are manufactured as cylindrical sleeves slightly smaller than the metal tubing they join. Their diameters are then expanded while martensitic, and upon warming to austenite, they shrink in diameter and strongly hold the tube ends. The tubes prevent the coupling from fully recovering its manufactured shape, and the stresses created as the coupling attempts to do so are great enough to create a joint that, in many ways, is superior to a weld.

Superelastic devices are used for applications that demand the extraordinary flexibility of NiTi. Nickel-titanium has the ability to absorb large amounts of strain energy and release it as the applied strain is removed. The elasticity of NiTi is approximately ten times that of steel. Nickel-titanium also has excellent torqueability and kink resistance, which are important for medical guidewires. Further, superelastic NiTi alloys provide a constant force over a large strain range. This has been exploited in the field of orthodontics (arch wires) where a constant force enhances tooth movement with greater patient comfort. Eyeglass frames represent another important superelastic application.

The martensitic phase of NiTi has some unique properties that have made it an ideal material for many applications. First, the martensitic phase transformation has excellent damping characteristics due to the energy absorption characteristics of its twinned phase structure. Second, the martensitic form of NiTi has remarkable fatigue resistance. Finally, the martensitic phase is easily deformed, yet will recover its shape upon heating above its transformation temperatures. Examples of martensitic devices include vibration dampers, bendable surgical tools for open heart surgery, and highly fatigue resistant wires.

Copper-Base Alloys

Compositions and Properties. Commercial copper-base shape memory alloys are available in ternary Cu-Zn-Al and Cu-Al-Ni alloys or in their quaternary modifications containing manganese. Manganese depresses transformation temperatures of both Cu-Zn-Al and Cu-Al-Ni alloys and shifts the eutectoid to higher aluminum content. It often replaces aluminum for better ductility. Elements such as boron, cerium, cobalt, iron, titanium, vanadium, and zirconium are also added for grain refinement. Compositions of the Cu-Zn-Al alloys usually fall in the range of 10 to 30 wt% Zn and 5 to 10 wt% Al; Cu-Al-Ni alloys contain 11 to 14.5 wt% Al and 3 to 5 wt% Ni. The martensitic transformation temperatures can be adjusted by varying chemical composition. Table 2 lists the major properties of copper-base SMAs.

Table 2 Properties of copper-base shape memory alloys

Property	Property value	
	Cu-Zn-Al	**Cu-Al-Ni**
Thermal properties		
Melting temperature, °C (°F)	950-1020 (1740-1870)	1000-1050 (1830-1920)
Density, g/cm^3 (lb/in.^{3})	7.64 (0.276)	7.12 (0.257)
Resistivity, μΩ · cm	8.5-9.7	11-13
Thermal conductivity, W/m · °C (Btu/ft · h · °F)	120 (69)	30-43 (17-25)
Heat capacity, J/kg · °C (Btu/lb · °F)	400 (0.96)	373-574 (0.089-0.138)
Mechanical properties		
Young's modulus, GPa (10^6 psi)(a)		
β phase	72 (10.4)(a)	85 (12.3)(a)
Martensite	70 (10.2)(a)	80 (11.6)(a)
Yield strength, MPa (ksi)		
β phase	350 (51)	400 (58)
Martensite	80 (11.5)	130 (19)
Ultimate tensile strength, MPa (ksi)	600 (87)	500-800 (73-116)
Shape memory properties		
Transformation temperatures, °C (°F)	<120 (250)	<200 (390)
Recoverable strain, %	4	4
Hysteresis, Δ°C (Δ°F)	15-25 (30-45)	15-20 (30-35)

(a) The Young's modulus of shape memory alloys becomes difficult to define between the M_s and the A_s transformation temperatures. At these temperatures, the alloys exhibit nonlinear elasticity, and the modulus is both temperature and strain dependent.

Processing. The melting of copper-base shape memory alloys is similar to that of aluminum bronzes. Most commercial alloys are induction melted. Protective flux on the melt and the use of nitrogen or inert-gas shielding during pouring are necessary to prevent zinc evaporation and aluminum oxidation. Powder metallurgy and rapid solidification processing are also used to produce fine-grain alloys without grain-refining additives.

Copper-base alloys can be readily hot worked in air. With low aluminum content (<6 wt%), Cu-Zn-Al alloys can be cold finished with interpass annealing. Alloys with higher aluminum content are not as easily cold workable. Cu-Al-Ni alloys, conversely, are quite brittle at low temperatures and can only be hot finished.

Because copper-base shape memory alloys are metastable in nature, solution heat treatment in the parent β-phase region and subsequent controlled cooling are necessary to retain βphase for shape memory effects. Prolonged solution heat treatment causes zinc evaporation and grain growth and should be avoided. Water quench is widely used as a quenching process, but air cooling can be sufficient for some high-cooling aluminum content Cu-Zn-Al alloys and Cu-Al-Ni alloys. The as-quenched transformation temperature is usually unstable. Postquench aging at temperatures above the nominal A_f temperature is generally needed to establish stable transformation temperatures.

Cu-Zn-Al alloys, when quenched rapidly and directly into the martensitic phase, are susceptible to the martensite stabilization effect. This effect causes the reverse transformation to shift toward higher temperatures. It therefore delays and can completely inhibit the shape recovery. For alloys with M_s temperatures above the ambient, slow cooling or step quenching with intermediate aging in the parent β-phase state should be adopted.

The thermal stability of copper-base alloys is ultimately limited by the decomposition kinetics. For this reason, prolonged exposure of Cu-Zn-Al and Cu-Al-Ni alloys at temperatures above 150 °C (300 °F) and 200 °C (390 °F), respectively, should be avoided. For high-temperature stability, Cu-Al-Ni is generally a better alloy system than Cu-Zn-Al. However, even for moderate temperature applications, which demand tight control of transformation temperatures, these effects need to be evaluated.

Applications. Similar to the NiTi hydraulic coupling described previously, a Cu-Zn-Al coupling for copper and aluminum tubing has been developed. In this application, the Cu-Zn-Al shape memory cylinder shrinks on heating and acts as a driver to squeeze a tubular liner onto the tubes being joined. The joint strength is enhanced by a sealant coating on the liner.

The Cu-Zn-Al shape memory alloys have also found several applications in the force actuation device area. One such example is a fire safety valve that incorporates a Cu-Zn-Al actuator designed to shut off toxic or flammable gas flow when fire occurs.

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Fusible Alloys

Introduction

FUSIBLE ALLOYS include a group of binary, ternary, quaternary, and quinary alloys containing bismuth, lead, tin, cadmium, and indium. The term fusible alloy refers to any of the more than 100 white-metal alloys that melt at relatively low temperatures, that is, below the melting point of tin-lead eutectic solder (183 °C, or 360 °F). The melting points of these alloys range as low as 47 °C (116 °F). Fusible alloys are used for lens blocking tube bending, for anchoring chucks and fixtures, and for mounting thin sections such as gas turbine blades for machining. The eutectic fusible alloys, which can be tailored to give a specific melting point find application in temperature control devices and in fire protection devices such as sprinkler heads.

Compositions and Properties

Compositions. Many of the fusible alloys used in industrial applications are based on eutectic compositions (Table 1). Under ambient temperature, such an alloy has sufficient strength to hold parts together; at a specific elevated temperature, however, the fusible alloy link will melt, thus disconnecting the parts. In fire sprinklers, the links melt when dangerous temperatures are reached, releasing water from piping systems and extinguishing the fire. Boiler plugs and furnace controls react similarly because an increase in temperature beyond the safety limits of the furnace or boiler operation will melt the plug. When the fusible alloy link melts, pressure or heat in the boiler can be dissipated, or feeding of the fuel supply can be ceased, thereby reducing operation to a safe level.

Table 1 Compositions and melting temperatures of selected eutectic fusible alloys

Composition, %					Melting temperature	
Bi	**Pb**	**Sn**	**Cd**	**Other**	**°C**	**°F**
44.70	22.60	8.30	5.30	19.10 In	47	117
49.00	18.00	12.00	. . .	21.00 In	58	136
50.00	26.70	13.30	10.00	. . .	70	158
51.60	40.20	. . .	8.20	. . .	91.5	197
52.50	32.00	15.50	. . .	. . .	95	203
54.00	. . .	26.00	20.00	. . .	102.5	217
55.50	44.50	. . .	. . .	. . .	124	255
58.00	. . .	42.00	. . .	. . .	138.5	281
. . .	30.60	51.20	18.20	. . .	142	288
60.00	. . .	. . .	40.00	. . .	144	291
. . .	. . .	67.75	32.25	. . .	177	351
. . .	38.14	61.86	. . .	. . .	183	362
. . .	. . .	91.00	. . .	9.00 Zn	199	390
. . .	. . .	96.00	. . .	3.50 Ag	221	430
. . .	79.7	. . .	17.7	2.60 Sb	236	457
. . .	87.0	. . .	. . .	13.00 Sb	247	477

In addition to eutectic alloys, each of which melts at a specific temperature, there are numerous noneutectic fusible alloys, which melt over a range of temperatures. Table 2 lists selected eutectic alloy compositions.

Table 2 Compositions, yield temperatures, and melting temperature ranges of selected noneutectic fusible alloys

Composition, %					Yield temperature		Melting temperature range	
Bi	**Pb**	**Sn**	**Cd**	**Other**	**°C**	**°F**	**°C**	**°F**
50.50	27.8	12.40	9.30	. . .	70.5	159	70-73	158-163
50.00	34.5	9.30	6.20	. . .	72	162	70-79	158-174
50.72	30.91	14.97	3.40	. . .	72.5	163	70-84	158-183
42.50	37.70	11.30	8.50	. . .	72.5	163	70-90	158-194
35.10	36.40	19.06	9.44	. . .	75	167	70-101	158-214
56.00	22.00	22.00	. . .	. . .	96	205	95-104	203-219
67.00	16.00	17.00	. . .	. . .	96	205	95-149	203-300
33.33	33.34	33.33	. . .	. . .	101	214	101-143	214-289
48.00	28.50	14.50	. . .	9.00 Sb	116	241	103-227	217-440
40.00	. . .	60.00	. . .	. . .	150	302	138-170	281-338
48.0	25.63	12.77	9.60	. . .	. . .	. . .	61-65	142-149

A fusible alloy with a long melting range is useful in staking rods and tubing in assemblies because the alloy is distributed around part surfaces while still molten and provides a firm anchorage after it solidifies.

Properties of Fusible Alloys. Fusible alloys are ageable, and thus their mechanical properties often depend on the period of time that has elapsed since casting, as well as on casting conditions and the solidification rate. Test conditions also affect mechanical property values. For example, many fusible alloys can appear brittle when subjected to sudden shock but exhibit high ductility under slow rates of strain.

In certain alloys, normal thermal contraction due to cooling after solidification can be partly, completely, or more than compensated for by expansion due to aging. For example, bismuth alloys containing 33 to 66% Pb exhibit net expansion after solidification and during subsequent aging. Some fusible alloys show no contraction (shrinkage) and expand rapidly while still warm; others show slight shrinkage during the first few minutes after solidification and then begin to expand; in still others, expansion does not commence until some time after the fusible alloy casting has cooled to room temperature.

Each of the three characteristics--net expansion, net contraction, and little or no volume change--can provide specific advantages, depending on the application. For example, a wood pattern used for making molds must be of somewhat greater dimensions than those desired in the casting to compensate for shrinkage of the casting on solidification and during cooling to room temperature. Where metal patterns are cast from a master wood pattern, two such allowances will have to be made unless the alloy used for the metal patterns possesses zero shrinkage. Fusible alloys with eutectic compositions are often used for casting metal patterns from wood masters because they undergo definite growth that is sufficient to allow for cleaning of production castings without reduction dimensions below required values. The growth characteristics of fusible alloys are often used to advantage when a metal part is to be firmly anchored in the lathe chuck. After the part is machined, the fusible alloys is melted away.

In general, the load-bearing capacity of fusible alloys is good, although some deformation will occur under prolonged stress. In addition, hardness and other mechanical properties of many fusible alloys change gradually with time, probably because of the same microstructural changes caused by aging that affect growth or shrinkage.

Low-melting, fusible alloy solders, which contain from 44.7 to 58 wt% Bi (see eutectic composition in Table 1), are used for soldering processes that involve temperature-sensitive substrates or devices, as well as step soldering operations where a low temperature is necessary to protect a nearby solder joint. Their ability to melt at low temperatures makes these material ideal for use in such applications as:

- Construction of temperature-overload devices such as safety links, fuses, and plugs where positive-pressure contact is too variable or inconsistent for assembly operation.
- Soldering low-temperature alloys such as pewter
- Machine-soldering operations for through-hole soldering of very thick multilayer printed circuit boards.
- Assembly operations, such as surface mounting, where the integrated circuit packages would be vulnerable to thermal damage at the temperatures required for conventional tin-lead soldering

- Assembly operations using injection-molded circuit boards where the glass transition temperature is too low for the use in tin-lead alloys.

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Hardfacing Alloys

Introduction

HARDFACING can be broadly defined as the application of a wear-resistant material, in depth, to the vulnerable (or worn) surfaces of a component by a weld overlay or thermal spray process. This article deals with the weld overlay materials used to resist wear; the thermal spray materials are covered in the Section "Surface Engineering" in this Handbook.

Hardfacing applications for wear control vary widely, ranging from very severe abrasive wear service, such as rock crushing and pulverizing (metal-to-earth applications/wear) to applications to minimize metal-to-metal wear, such as control valves where a few thousandths of an inch of wear is intolerable. Hardfacing is used for controlling abrasive wear, such as that encountered by mill hammers, digging tools, extrusion screws, cutting shears, parts of earth-moving equipment, ball mills, and crusher parts. It is also used to control the wear of unlubricated or poorly lubricated metal-to-metal sliding contacts such as control valves, undercarriage parts of tractors and shovels, and high-performance bearings.

Hardfacing is also used to control combinations of wear and corrosion, as encountered by mud seats, plows, knives in the food processing industry, and valves and pumps handling corrosive liquids or slurries. In most instances, parts are made of either plain carbon steel or stainless steel, materials that do not provide desirable wear on their own.

In addition, hardfacing alloys are applied to critical wear areas of original equipment or during reclamation of parts. These alloys, which are referred to as buildup alloys, are not designed to resist wear but to return a worn part back to, or near, its original dimensions and/or to provide adequate support for subsequent layers of more wear-resistant hardfacing alloys.

Hardfacing Materials

Hardfacing materials include a wide variety of alloys, carbides, and combinations of these materials. Conventional hardfacing materials are normally classified as steels or low-alloy ferrous materials, high-chromium white irons or high-alloy ferrous materials, carbides, nickel-base alloys, or cobalt-base alloys. A few copper-base alloys are sometimes used for hardfacing applications, but for the most part, hardfacing alloys are either iron-, nickel-, or cobalt-base.

Several welding processes are used to apply the hardfacing materials. They range from the traditional (for example, oxyacetylene torch) to more recently developed processes like plasma-transferred arc. To accommodate these different overlay processes, the hardfacing materials are available in a variety of forms. The most popular processes, and the forms most commonly associated with each process, are:

Weld overlay process	Consumable form
Oxyacetylene	Bare cast or tubular rod
Shielded metal arc (SMA)	Coated solid or tubular rod (stick electrode)
Gas tungsten arc (GTA)	Bare cast or tubular rod
Gas metal arc (GMA)	Tubular or solid wire
Open arc	Tubular wire (flux cored)
Submerged arc	Tubular or solid wire
Plasma-transferred arc (PTA)	Powder

In choosing the process to be used, the following factors are important:

- Deposition rate
- Level of dilution (the amount of substrate material intermixed with the overlay material during welding)
- Portability of equipment

To overcome the effects of dilution on wear properties, multiple layers are often employed.

Microstructurally, hardfacing alloys generally consist of hard phase precipitates such as borides, carbides, or intermetallics bound in a softer iron-, nickel-, or cobalt-base alloy matrix. Carbides are the predominant hard phases in iron- and cobalt-base hardfacing alloys. Carbon contents of iron- and cobalt-base hardfacing alloys generally range up to 4 wt%. Borides, as well as carbides, are the predominant hard phases in nickel-base hardfacing alloys. Combined carbon plus boron contents generally range up to 5 wt%. The specific carbide and/or boride phases that form are determined by matrix alloy additions. The matrix alloys in most cobalt-, nickel-, and high-alloy, iron-base hardfacing alloys generally contain up to 35% Cr, up to 30% Mo, and up to 13% W, with smaller amounts of silicon and manganese.

Iron-Base Alloys

Iron-base hardfacing alloys are more widely used than cobalt- and/or nickel-base hardfacing alloys and constitute the largest volume use of hardfacing alloys. Iron-base hardfacing alloys offer low cost and a broad range of desirable properties. Most equipment that undergoes severe wear, such as crushing and grinding equipment and earthmoving equipment, is usually very large and rugged. Parts subjected to wear usually require downtime for repair. For this reason, there is a general temptation to hardface them with the lowest cost and most readily available materials. As a result, literally hundreds of iron-base hardfacing alloys are in use today.

Due to the great number of alloys involved, iron-base hardfacing alloys are best classified by their suitability for different types of wear and their general microstructures rather than by chemical composition. Most iron-base hardfacing alloys can be divided into the following classes:

- Pearlitic steels
- Austenitic (manganese) steels
- Martensitic steels
- High-alloy irons
- Austenitic stainless steel

Pearlitic steels are essentially low-alloy steels with minor adjustments in composition to achieve weldability. These alloys contain low carbon (<0.2% C) and low amounts of other alloying elements (for example, up to 2% Cr), resulting in a pearlitic structure. Pearlitic steels are useful as buildup overlays, primarily to rebuild carbon steel or low-alloy steel machinery parts back to size. Typically, this group of alloys has high impact resistance and low hardness (in the range of 25 to 37 HRC), as well as excellent weldability. Table 1 lists the composition and properties of a typical low-alloy pearlitic steel (EFe1) used for buildup applications.

Table 1 Compositions, hardness, and abrasion data for a pearlitic low-alloy steel (EFe1) and austenitic manganese steels (EFeMn-C and EFeMn-Cr) used for buildup overlays and air-hardening martensitic steels used for metal-to-metal wear applications

Alloy	Composition, wt%							Hardness, HRC	Abrasion, volume loss			
									Low-stress(a)		**High-stress**(b)	
	Fe	**Cr**	**C**	**Si**	**Mn**	**Mo**	**Ni**		**mm^3**	**in.^{3} × 10^{-3}**	**mm^3**	**in.^{3} × 10^{-3}**
Buildup weld overlay												
EFe1(c)	bal	2	0.1	1.0	1	1.5	. . .	37	88	5.4	49	3.0
EFeMn-C(c)	bal	4	0.8	1.3	14	. . .	4	18	65	4.0	57	3.5
EFeMn-Cr(c)	bal	15	0.5	1.3	15	2.0	1	24	93	5.7	46	2.8
Metal-to-metal weld overlay												
EFe2(c)	bal	3	0.2	1.0	1	1.0	1	48	54	3.3	66	4.0
EFe3(c)	bal	6	0.7	1.0	1	1.0	. . .	59	60	3.7	68	4.1
ER420(d)	bal	12	0.3	1.0	2	. . .	. . .	45	84	5.1	62	3.8

(a) Dry sand/rubber wheel test (ASTM G 65, Procedure B): load 13.6 kg (30 lb); 200 rev.

(b) Slurry/steel wheel test (ASTM B 611, modified): load 22.7 kg (50 lb); 250 rev.

(c) Two-layer shielded metal arc deposit process.

(d) Two-layer submerged arc welding deposit process

Austenitic (manganese) steels are modeled after Hadfield steels. Most commercially available alloys in this category can be broadly subdivided into low-chromium and high-chromium alloys.

Low-chromium alloys usually contain up to 4% Cr and 12 to 15% Mn and some nickel or molybdenum (Table 1). Low-chromium austenitic manganese steels generally are used to build up manganese steel machinery parts subjected to high impact (impact crusher or shovel lips).

High-chromium austenitic steels, which may normally contain 12 to 17% Cr in addition to approximately 15% Mn, are used for the buildup and joining of austenitic manganese steels as well as carbon and low-alloy steels. In addition, the as-deposited hardness of high-chromium steels is higher (~24 HRC) than that of low-chromium steels (~18 HRC). Compositions and properties of austenitic manganese steel hardfacing alloys used for buildup applications are given in Table 1.

Martensitic steels are designed to form martensite on normal air cooling of the weld deposit. As a result, these steels are often termed "self-hardening" or "air-hardening," and they resemble tool steels with hardnesses in the range of 45 to 60 HRC. The carbon content of the martensitic steels ranges up to 0.7%. Other elements such as molybdenum, tungsten, nickel, and chromium (up to 12%) are added to increase hardenability and strength and to promote martensite formation. Manganese and silicon usually are added to aid weldability. Table 1 lists compositions and properties of martensitic steels.

The major hardfacing applications for martensitic steels include unlubricated metal-to-metal rolling or sliding parts. The impact resistance of martensitic steels is inferior to that of pearlitic or austenitic alloys, but there is a compensating increase in hardness and resistance to abrasive wear.

In hostile environments, a higher chromium content is beneficial. AWS ER420 and modified versions containing nickel, molybdenum, and niobium (or vanadium) are therefore the natural choice when high temperatures and mildly corrosive environments are encountered. For applications using steel mill hot-work rolls (which demand considerable hot hardness, resistance to oxidation, and resistance to thermal fatigue) both ER420 and EFe3 have been found suitable.

The high-chromium irons encompass a wide range of compositions in which chromium may vary between approximately 6 and 35 wt%, and carbon may vary from approximately 2 to 6 wt%. Other possible alloying additions include molybdenum, manganese, and silicon. Table 2 lists typical compositions.

Table 2 Composition of high-chromium white irons used for metal-to-earth abrasion applications

Alloy	Composition, wt%							
	Cr	**C**	**Si**	**Mn**	**Mo**	**Ni**	**B**	**Fe**
ERFeCr-A3	11	2.6	1.3	1.8	1.5	. . .	. . .	bal
ERFeCr-A4(Mod)	29	3.5	1.1	0.9	. . .	2.6	0.7	bal
ERFeCr-A2	28	4.3	0.8	1.7	1.4	. . .	. . .	bal

The most important microstructural feature in the high-chromium irons, at least from a wear standpoint, is an M_7C_3 carbide, which forms in abundance during solidification and contains chromium, iron, and (if present) molybdenum. The matrix around these carbide particles can be austenitic, pearlitic, or martensitic.

With regard to industrial applications of the high-chromium abrasion alloys, the low-carbon (2 to 3% C) hypoeutectic materials are usually selected for situations involving moderate abrasion and impact, whereas the higher-carbon (4 to 6% C) hypereutectic alloys are used in applications involving severe abrasion and little or no impact. The hardness range for high-chromium irons is typically 52 to 62 HRC.

Austenitic stainless steel hardfacing alloys have been developed, which can be considered alternative materials to the cobalt-base alloys described below. These exhibit similar anti-galling characteristics and possess equal resistance to cavitation erosion. Some of these have been developed for general use and others for specific applications. For example, the cobalt-free composition in Table 3 has been used for hardfacing nuclear plant valves (Co^{60} produced from cobalt hardfacing wear particles pose a radiation hazard). Cobalt-containing austenitic grades (Table 3) have been used for the repair of the cavitation damage of hydraulic turbines in hydroelectric power plants.

Table 3 Nominal compositions of austenitic stainless steel hardfacing alloys

Alloy	Composition, %							
	C	**Cr**	**Mn**	**Si**	**Ni**	**Mo**	**Co**	**N**	**Fe**
NOREM[(a)]	0.7-1.3	24-26	5-12	2.5-5	5-9	. . .	1.7-2.3	0.05-0.24	bal

(a) Developed by the Electric Power Research Institute.

(b) Developed by Hydro-Québec. IRECA denotes Improved REsistance to CAvitation.

Nonferrous Alloys

Nonferrous hardfacing alloys are used either for high resistance to specific types of wear (other than abrasion) or for wear resistance (including abrasion) in environments that are too corrosive or beyond the service temperature of ferrous alloys. The cobalt-base alloys and bronzes are particularly resistant to galling and to those wear processes involving microfatigue as the degradation mechanism (such as cavitation erosion). The cobalt-base alloys also possess high resistance to deformation at temperatures in excess of 750 °C (1380 °F). Table 4 lists typical compositions of the nonferrous hardfacing alloys.

Table 4 Composition of selected nonferrous hardfacing alloys

Alloy	Composition, wt%										
	Fe	**Cr**	**Mo**	**W**	**Si**	**C**	**B**	**Al**	**Cu**	**Co**	**Ni**
Cobalt-base/carbide type											
ERCoCr-A	...	28	...	5	...	1.2	...	...	...	bal	...
ERCoCr-B	...	29	...	8	...	1.5	...	...	...	bal	...
ERCoCr-C	...	31	...	13	...	2.5	...	...	...	bal	...
ERCoCr-E	...	27	6	...	...	0.2	...	...	...	bal	...
Cobalt- and nickel-base/Laves type											
T-400	...	9	29	...	2.5	...	...	...	...	bal	...
T-700	...	16	33	...	3.5	...	...	...	...	...	bal
T-800	...	18	29	...	3.5	...	...	...	...	bal	...
Nickel-base/boride type											
Alloy 40	1.5	7.5	...	...	3.5	0.3	1.5	...	...	...	bal
ERNiCr-B	3	11	...	...	4	0.5	2.5	...	...	...	bal
ERNiCr-C	4	16	...	...	4	0.7	3.5	...	...	...	bal
Aluminum bronze type											
ECuAl-B	4	...	...	...	1.0	...	...	9	bal	...	...
ECuAl-D	4	...	...	...	...	...	...	13.5	bal	...	...

Cobalt-Base/Carbide-Type Alloys. The chief difference between the various cobalt-base/carbide-type alloys is in carbon content (hence, carbide volume fraction, room-temperature hardness, and level of abrasion resistance). Chromium-rich M_7C_3 is the predominant carbide in these alloys, although tungsten-rich M_6C is evident in those alloys having a high tungsten content, and chromium-rich $M_{23}C_6$ is common in the low-carbon alloys. Hardness values for cobalt-base/carbide-type alloys range from approximately 40 to 55 HRC. As shown in Fig. 1, the abrasion resistance of these alloys (ERCoCr-A, -B, -C, and -E) increases with increasing carbon content.

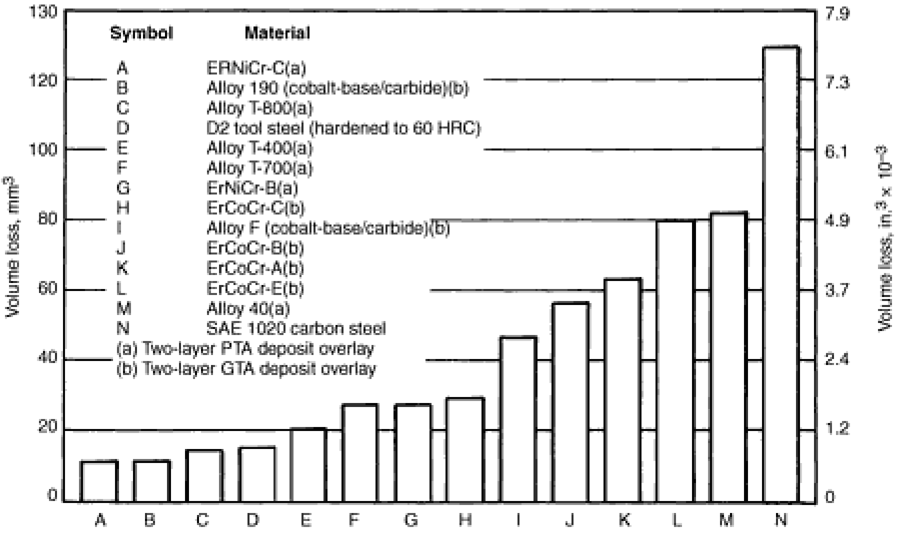

Fig. 1 Comparison of nonferrous hardfacing alloys to tool steel and carbon steel reference materials using ASTM G 65 low-stress, abrasion test. G 65 test parameters: procedure B; room temperature; 13.6 kg (30 lbf) load; quartz grain sand diameter of 212 to 300 μm; 2000 rev at 200 rev/min; 390 g/min (0.86 lb/min) feed rate

Laves Phase Alloy Compositions. Laves phase is a type of topologically close-packed intermetallic compound. Historically, metallurgists have avoided the presence of Laves phase in most alloys due to its detrimental effect on mechanical properties. However, in the 1960s, the usefulness of Laves phase in resisting metal-to-metal wear was discovered; subsequently, alloys containing Laves phase have become commercially available.

As shown in Table 4, there are two Laves phase cobalt-base alloys available for hardfacing applications (Co-29Mo-9Cr-2.5Si and Co-29Mo-18Cr-3.5Si). Both of these alloys contain at least 50 vol% of Laves phase. Laves phase has a hardness value between 1000 and 1200 DPH, which is less than that of carbides. Consequently, the Laves phase-containing alloys are less abrasive to mating materials than carbide-containing alloys in metal-to-metal wear situations.

Hardness values for cobalt-base Laves phase alloys range from 54 to 64 HRC. The nickel-base Laves phase alloy (Ni-33Mo-16Cr-3.5Si in Table 4) has a nominal macrohardness of 45 HRC. Abrasion data for Laves phase alloys are given in Fig. 1. Although these alloys have been deposited by weld techniques, they are more frequently applied by thermal spray methods.

Nickel-base/boride-type alloy compositions represent a progression in terms of iron, chromium, boron, and carbon contents (Table 4). Iron content is largely incidental, allowing the use of ferrocompounds during manufacture. Together with nickel, the other three elements determine the level and type of hard phase within the structure upon solidification, with boron being the primary hard-phase forming element. Hardness values for boride-containing nickel alloys range from 51 to 57 HRC.

Because of the boride and carbide dispersions within their microstructures, the nickel-base/boride-type alloys exhibit excellent resistance to abrasion (ERNiCr-C, ERNiCr-B, and Alloy 40 in Fig. 1). Low-stress abrasion resistance generally increases with boron and carbon contents, hence the hard-phase volume fraction for these materials. Although their performance is not as good under self-mated sliding conditions as the cobalt-base materials, the nickel-base/boride-type alloys possess moderate resistance to galling. Of the nonferrous materials, the nickel-base/boride-type alloys are the least resistant to corrosion. This is attributed to the lack of chromium in the matrix.

Bronze Type. The two bronze compositions given in Table 4 fall in the aluminum bronze category. Silicon and other types of bronze also available in welding consumable form for hardfacing.

Components typically protected using the aluminum bronzes include gears, cams, and cold drawing/forming dies. These alloys are not recommended for elevated-temperature use because their mechanical properties considerably decrease at temperatures >200 °C (>390 °F).

Tungsten Carbides

In contrast to the other weld overlay materials, the tungsten carbide composites do not rely on the formation of suitable hard phases during weld pool solidification. Instead, these overlay materials rely on the transfer of tungsten carbide particles from the welding consumable (carbides are inserted in a steel tube) to the overlay. It is important, therefore, to limit the heat input of the welding process in order to prevent melting of the tungsten carbide particles. If the tungsten carbide particles melt, they mix with iron to form much softer iron-tungsten carbides, thus reducing abrasion resistance. For this reason, oxyacetylene deposits usually exhibit higher abrasion resistance than arc-welded tungsten carbide overlays.

An advantage of the tungsten carbide composites is that the size of the hard particles in the overlay can be controlled. This is important because abrasion resistance is dependent upon the size relationship between microstructural features (such as carbides) and the abrading particles. If the abrading particles are large in comparison to the microstructural particles, then, after a running-in period (during which the softer matrix material at the surface is worn down), the abrading particles ride over the hard microstructural outcrops. Conversely, if the abrading particles are small in comparison to the microstructural particles, the opportunity exists for wear of the matrix around the microstructural particles. Eventually, these may drop out, having played only a small role in resisting abrasion.

Several tungsten carbide composites are available in a variety of tubular product forms. Popular compositions are 38, 50, 55, and 60 wt% tungsten carbide, with the carbon steel tube making up the balance. For each composition, several carbide size ranges are available. As an example, for the 60% WC oxyacetylene welding consumable, four mesh size ranges are available:

AWS designation	Mesh size range
RWC-12/20	12-20
RWC-20/30	20-30
RWC-30/40	30-40
RWC-40/120	40-120

The same composition is also available in flux-coated form for shielded metal arc welding (SMAW) and as a continuous wire (with an internal flux) for open arc welding.

Tungsten carbide composites generally possess very high resistance to abrasion and very low impact strength. Performance in a given situation is dependent upon (a) carbide volume fraction, (b) size relationship between the carbides and the abrasive medium, and (c) welding technique applied. Important factors are the distribution of carbides in the overlay (because the particles tend to sink, turbulence in the molten weld pool is an advantage), and the amount of carbide dissolution and reprecipitation in the steel matrix during welding. Impact strength generally decreases with increasing carbide volume fraction.

The tungsten carbide composites have been used to solve a wide variety of industrial sliding and drilling abrasion problems. Table 5 gives abrasion data. For extremely hostile environments, some non-ferrous tungsten carbide products (cobalt- and nickel-base products in the form of bare cast rods) are available. Also, several alternative composite materials, utilizing other carbides (for example, vanadium, titanium, or niobium), are available that have the advantage of creating a more homogeneous deposit because of their lower densities.

Table 5 Abrasion data for tungsten carbide composites

Material		Abrasion, volume loss			
Carbide, wt %	**Mesh size**	**Low-stress**(a)		**High-stress**(b)	
		mm^3	**in.^{3} × 10^{-3}**	**mm^3**	**in.^{3} × 10^{-3}**
60	20-30	7.3	0.45	28.7	1.75

(a) Dry sand/rubber wheel test (ASTM G 65, Procedure B): load 13.6 kg (30 lb); 2000 rev.

(b) Slurry/steel wheel test (ASTM B 611, modified): load 22.7 kg (50 lb); 250 rev

Selected References

- P. Crook and H.N. Farmer, Friction and Wear of Hardfacing Alloys, *Friction, Lubrication, and Wear Technology,* Vol 18, *ASM Handbook,* ASM International, 1992, p 758-765
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Metal-Matrix Composites

Introduction

METAL-MATRIX COMPOSITES (MMCs) are a class of materials with potential for a wide variety of structural and thermal management applications. Metal-matrix composites are capable of providing higher-temperature operating limits than their base metal counterparts, and they can be tailored to give improved strength, stiffness, thermal conductivity, abrasion resistance, creep resistance, or dimensional stability. Unlike polymer-matrix composites, they are nonflammable, do not outgas in a vacuum, and suffer minimal attack by organic fluids such as fuels and solvents.

In an MMC, the matrix phase is a monolithic alloy (usually a low-density nonferrous alloy) and the reinforcement consists of high-performance carbon, metallic, or ceramic additions. Reinforced intermetallic compounds, such as the aluminides of titanium, nickel, and iron, are also under development. Reinforcements, characterized as either continuous or discontinuous, may constitute from 10 to 70 vol% of the composite. Continuous fiber or filament (f) reinforcements include graphite, silicon carbide (SiC), boron, aluminum oxide (Al_2O_3), and refractory metals. Discontinuous reinforcements consist mainly of SiC in whisker (w) form, particulate (p) types of SiC, Al_2O_3, and titanium diboride (TiB_2), and short or chopped fibers (c) of Al_2O_3 or graphite.

Aluminum-Matrix Composites

Most of the commercial work on MMCs has focused on aluminum as the matrix metal. The combination of light weight, environmental resistance, and useful mechanical properties has made aluminum alloys very popular; these properties also make aluminum well suited for use as a matrix metal. The melting point of aluminum is high enough to satisfy many application requirements, yet low enough to render composite processing reasonably convenient. Also, aluminum can accommodate a variety of reinforcing agents. Although much of the early work on aluminum MMCs concentrated on continuous fiber types, most of the present work is focused on discontinuously reinforced (particle or whisker) aluminum MMCs because of their greater ease of manufacture, lower production costs, and relatively isotropic properties. As shown in Fig. 1, however, higher performance composites are produced by more expensive, continuous fiber reinforcements. At the opposite end of the cost/performance spectrum are the particle-reinforced molten (or cast) metal composites. In between lie medium-priced composites, including those produced by preform infiltration and powder metallurgy (P/M) techniques.

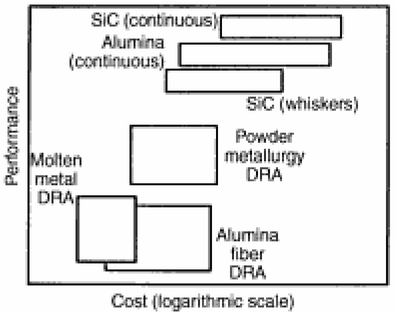

Fig. 1 The material cost versus performance of various aluminum-matrix composites. DRA, discontinuously reinforced aluminum

Aluminum MMC Designation System

Because more aluminum MMCs are produced than MMCs of all other matrix alloys combined, the Aluminum Association (AA) developed a standard designation system for MMCs that has since been adopted by the American National Standards Institute. ANSI 35.5-1992 provides that aluminum MMCs be identified as follows:

matrix/reinforcement/volume%form

For example, 2124/SiC/25w describes the AA-registered alloy 2124 reinforced with 25 vol% of silicon carbide whiskers; 7075/Al_2O_3/10p is the AA-registered alloy 7075 reinforced with 10 vol% of alumina particles; 6061/SiC/47f is the AA-registered alloy 6061 reinforced with 47 vol% of continuous SiC fibers; and A356/C/05C is an AA-registered casting alloy with 5 vol% of chopped graphite fibers.

Discontinuous Aluminum MMCs

The most commonly used reinforcement materials in discontinuously reinforced aluminum composites are SiC and Al_2O_3, although silicon nitride (Si_3N_4), TiB_2, and graphite have also been used in some specialized applications. For example, aluminum-graphite alloys have been developed for tribological applications because of their excellent antifriction properties, wear resistance, and anti-seizure characteristics. Table 1 lists properties of materials used to reinforce aluminum alloys.

Table 1 Typical properties of particulate (p), whisker (w), and chopped fiber (c) reinforcements

Property	Reinforcement						
	SiC_p	**Al_2O_{3p}**	**TiB_{2p}**	**Si_3N_{4p}**	**Al_2O_{3c}**(a)	**SiC_w**(b)	**Si_3N_{4w}**
Density, g/cm^3	3.21	3.97	4.5	3.18	3.3	3.19	3.18
Diameter, μm	. . .	. . .	. . .	. . .	3-4	0.1-1.0	. . .
Coefficient of thermal expansion, $10^{-6} \cdot K^{-1}$	4.3-5.6	7.2-8.6	8.1	3.0	∼9	4.8	3.8
Tensile strength, MPa (ksi)	100-800(c) (14.5-116)(c)	70-1000(c) (10-145)(c)	700-100(c) (101.5-145)(c)	250-100(c) (36-145)(c)	>2000 (>290)	3,000-14,000 (435-2030)	13,800 (2,001)
Young's modulus, GPa (10^6 psi)	200-480 (29-70)	380 (55)	514-574 (75-83)	304 (44)	300 (43.5)	400-700 (58-101.5)	379 (55)
Elongation, %	. . .	. . .	. . .	. . .	0.67	1.23	. . .

(a) Saffil (96% Al_2O_3-4%SiO_2).

(b) >98% SiC.

(c) Transverse rupture strength of bulk

Processing methods for discontinuous aluminum MMCs include various casting processes: liquid-metal infiltration, spray deposition, and powder metallurgy. Each of these processes will be briefly reviewed in the following paragraphs.

Effect of Reinforcement on Properties. In MMCs, mechanical properties depend on the amount, size, shape, and distribution of the dispersed phase (reinforcement), apart from the mechanical properties of the matrix material, and on the nature of the interface. By definition, a composite material generally requires an amount of dispersed phase (>1 vol%) of a size (>1 μm) that allows this constituent to be load bearing and not act merely to control the movement of dislocations, as in dispersion-strengthened materials. The shape of the dispersed phase is so important in determining its load-bearing capacity that composites have been classified on this basis: (a) fiber-reinforced composites with both continuous and discontinuous fibers and (b) particle- or whisker-reinforced composites. The aspect ratio generally characterizes the shape. In continuous-fiber composites, the load is applied directly to both the matrix and the fiber. In discontinuous-fiber composites or particle-reinforced composites, the load is transmitted to the dispersoid through the matrix.

Property predictions of MMCs can be obtained from mathematical models, which require as input a knowledge of the properties and geometry of the constituents. Information on these mathematical expressions, which include simple rule of mixture models, can be found in the selected references listed at the conclusion of this article. In general, however, the influence of hard particle reinforcement (e.g., SiC) on the relevant mechanical and physical properties of discontinuous aluminum-MMCs can be summarized as follows:

- Both the ultimate tensile strength and yield strength increase with an increase in reinforcement fraction. (It should be noted that these properties are decreased with an increase in volume fraction of soft particles, e.g., graphite.)
- The fracture toughness and ductility (percent elongation and strain to failure) decrease with an increase in reinforcement volume fraction.
- The Young's modulus increases with an increase in reinforcement volume fraction.
- The thermal and electrical conductivities as well as the coefficient of thermal expansion decrease with increasing reinforcement volume fraction.

Figure 2 illustrates the effects of SiC volume fraction on the properties of discontinuous aluminum MMCs.

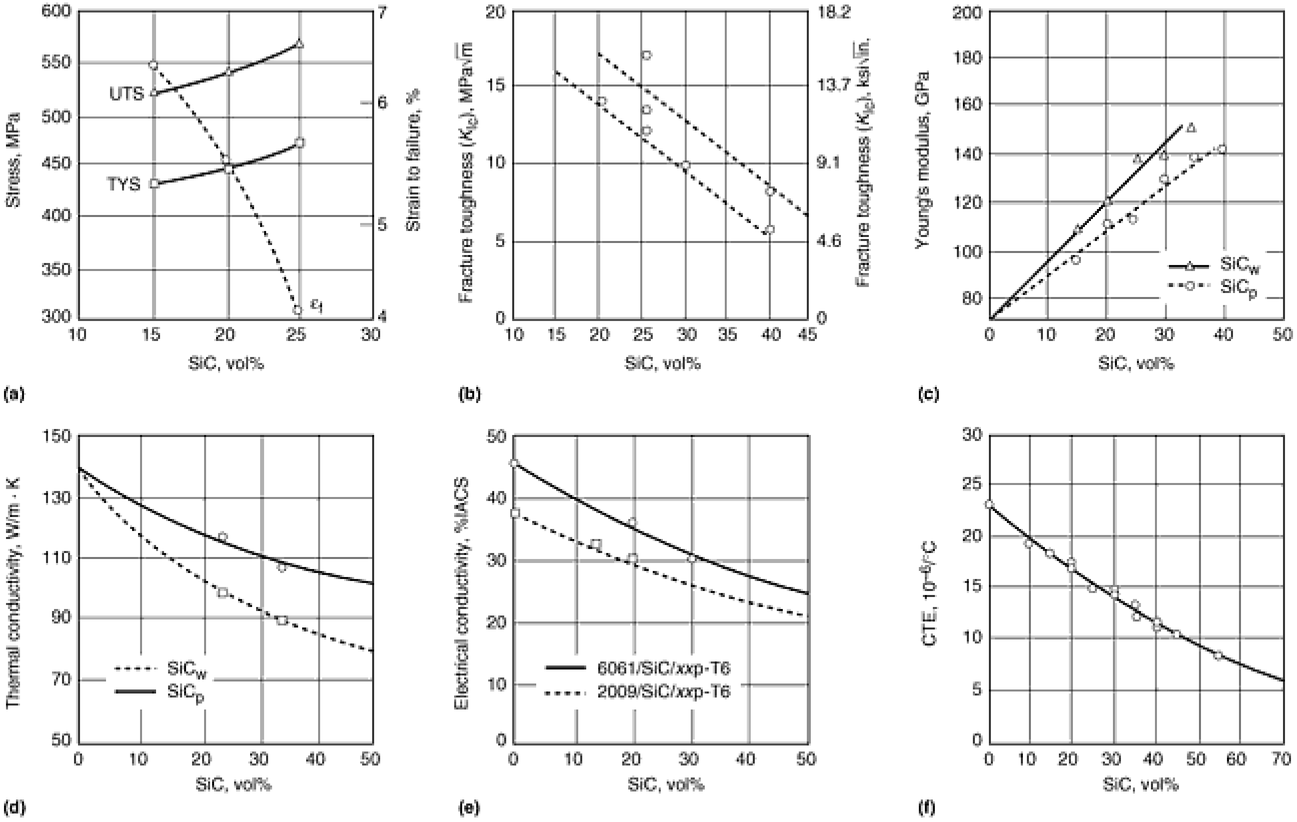

Fig. 2 Effect of reinforcement volume fraction on the properties of aluminum metal-matrix composite (MMCs). (a) The ultimate tensile strength (UTS), tensile yield strength (TYS), and strain-to-failure (ε_f) for 6013/SiC/*xx*p-T6. (b) Fracture toughness as a function of SiC volume fraction. (c) Young's modulus as a function of SiC$_w$ and SiC$_p$ volume fraction. (d) Thermal conductivity for 2009/SiC/*xx*-T6. (e) Electrical conductivity for 2009/SiC/*xx*p-T6 and 6061/SiC/*xx*p-T6. (f) Coefficient of thermal expansion (CTE) for 6061/SiC/*xx*p-T6.

Cast Aluminum MMCs. In the stir casting (or mixing/vortex), the pretreated and prepared reinforcement filler phase is introduced in a continuously stirred molten matrix and then cast by sand, permanent mold, or pressure die casting. Melting under an inert gas cover combined with Ar-SF_6 gas mixtures for fluxing and degassing is essential to avoid the entrapment of gases. Mixing can be affected ultrasonically or by reciprocating rods, centrifuging, or zero-gravity processing.

Matrix alloys include aluminum-silicon compositions specially designed for MMC processing (Table 2). Reinforcements include 10 to 20 μm sized SiC or Al_2O_3 particles in volume fractions ranging from 10 to 20%. Figure 3 shows a typical microstructure. Table 3 lists typical mechanical properties of high-pressure die cast aluminum MMCs. The automotive industry is behind the development of cast aluminum MMCs. Current or potential applications include brake rotors and drums, brake calipers, brake pad backing plates, and cylinder liners.

Table 2 Matrix alloys for discontinuous reinforced aluminum metal-matrix composites

Alloy	Composition, wt%									
	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Ni**	**Ti**	**Zn**	**Other**	**Al**
High-pressure die castings										
F3D(a)	9.50-10.5	0.80-1.20	3.00-3.50	0.50-0.80	0.30-0.50	1.00-1.50	0.20 max	0.03 max	0.03 max; 0.10 total	bal
F3N(b)	9.50-10.5	0.80-1.20	0.20 max	0.50-0.80	0.50-0.70	. . .	0.20 max	0.03 max	0.03 max; 0.10 total	bal
Sand and permanent mold castings										
F3S(c)	8.50-9.50	0.20 max	0.20 max	. . .	0.45-0.65	. . .	0.20 max	. . .	0.03 max; 0.10 total	bal
F3K(d)	9.50-10.5	0.30 max	2.80-3.20	. . .	0.80-1.20	1.00-1.50	0.20 max	. . .	0.03 max; 0.10 total	bal

Source: Duralcan USA

(a) Duralcan F3D*xx*S composites (*xx* = volume percent SiC particulate) are general-purpose, die-casting composites. They are similar to 380/SiC/*xx*p (Aluminum Association MMC nomenclature).

(b) Duralcan F3N*xx*S composites, containing virtually no copper or nickel, are designed for use in corrosion-sensitive applications. They are similar to 360/SiC/*xx*p.

(c) Duralcan F3S*xx*S composites (*xx* = volume percent SiC particulate) are general-purpose composites for room-temperature applications. They are similar to 359/SiC/*xx*p (Aluminum Association MMC nomenclature).

(d) Duralcan F3K*xx*S composites, containing significant amounts of copper and nickel, are designed for use at elevated temperatures. They are similar to 339/SiC/*xx*p.

Table 3 Typical mechanical properties for high-pressure die cast F3D/SiC composites

Material	Ultimate strength		Yield strength		Elongation(a), %	Elastic modulus		Hardness, HRB	Impact energy	
	MPa	**ksi**	**MPa**	**ksi**		**GPa**	**10^6psi**		**J**	**ft · lbf**
A380-F(b)	317	46.0	159	23.1	3.5	71.0	10.3	40	3.4	2.5
A390-F(b)	283	41.0	241	34.9	1.0	81.4	11.8	76	1.4	1.0
F3D.10S-F(c)	345	50.0	241	34.9	1.2	93.8	13.6	77	1.4	1.0
F3D.10S-O(d)	276	40.0	152	22.0	1.7	93.8	13.6	55	2.7	2.0
F3D.10S-T5(d)	372	53.9	331	48.0	0.7	93.8	13.6	84	1.4	1.0
F3D.20S-F(c)	352	51.0	303	43.9	0.4	113.8	16.5	82	0.7	0.5
F3D.20S-O(d)	303	43.9	186	27.0	0.8	113.8	16.5	62	1.4	1.0
F3D.20S-T5(e)	400	58.0	(f)	(f)	(f)	113.8	16.5	87	0.7	0.5

See Table 2 for composition of matrix alloy.

(a) Measured by direct reading from stress-strain plot.

(b) Handbook values.

(c) Cast-to-size tensile bars.

(d) Cast-to-size tensile bars, annealed at 343 °C (649 °F) for 4 h.

(e) Cast-to-size tensile bars, aged at 177 °C (351 °F) for 5 h.

(f) Test bars fractured before yielding.

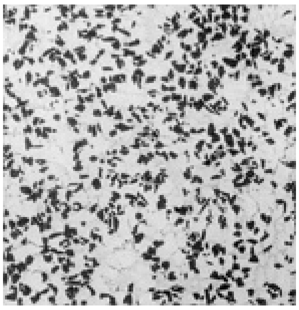

Fig. 3 Typical microstructure of an aluminum-matrix composite containing 20 vol% SiC. 125×

Aluminum MMCs produced by stir casting are also commonly extruded. Wrought composites currently available in extrusion billet include:

Composite	Al_2O_3 content, vol%
6061/Al_2O_3/*x*p	10, 15, or 20
2014/Al_2O_3/*x*p	10, 15, or 20
1060/Al_2O_3/*x*p	10
7005/Al_2O_3/*x*p	10
7075/Al_2O_3/*x*p	10

Room-temperature properties of extruded aluminum MMCs are given in Table 4.

Table 4 Room-temperature properties of extruded stir-cast aluminum MMCs in the T6 condition

Material	Al_2O_3 content, vol %	Ultimate strength				Yield strength				Tensile elongation, %	Elastic modulus		Fracture toughness	
		Typical		**Minimum**(a)		**Typical**		**Minimum**(a)						
		MPa	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**		**GPa**	**10^6psi**	**MPa$\sqrt{m}$**	**ksi$\sqrt{in.}$**
6061/Al_2O_3/*x*p	0	310	45	260	38	275	40	240	35	20	69.0	10.0	29.6	27.0
	10	350	51	325	47	295	43	260	38	10	81.4	11.8	24.0	21.9
	15	365	53	340	49	325	47	290	42	6	89.0	12.9	22.0	20.0
	20	370	54	345	50	350	51	315	46	4	97.2	14.1	21.5	19.6
2014/Al_2O_3/*x*p	0	525	76	470	68	475	69	415	60	13	73.1	10.6	25.3	23.0
	10	530	77	495	72	495	72	455	66	3	84.1	12.2	18.0	16.4
	15	530	77	495	72	505	73	460	67	2	93.8	13.6	18.8	17.1
	20	515	75	485	70	505	73	460	67	1	101	14.7	. . .	. . .

(a) Values represent 99% confidence interval

Squeeze-Cast Aluminum MMCs. Squeeze casting is a process by which molten metal solidifies under pressure within closed dies positioned between the plates of a hydraulic press. The applied pressure and the instant contact of the molten metal with the die surface produce a rapid heat transfer condition that yields a pore-free, fine-grain casting with mechanical properties approaching those of a wrought product.

Squeeze casting of aluminum MMCs involves placing a porous ceramic preform in the preheated die, which is later filled with the liquid metal; pressure is then applied. The pressure, in this case, helps the liquid metal infiltrate the porous ceramic preform, giving a sound metal-ceramic composite.

Squeeze casting has attracted much attention because the process minimizes material and energy use, produces net shape components, and offers a selective reinforcement capability. Both discontinuous and continuous aluminum-copper, aluminum-silicon, and aluminum-magnesium alloys reinforced with up to 45 vol% SiC have been produced.

Rheocast Aluminum MMCs. Rheocasting, also referred to as compocasting, is similar to the metal stirring route, but instead of the particulates being stirred into a fully liquid metal, it is stirred in the semi-solid (thixotropic) state and subsequently cast under pressure. Particles and discontinuous fibers of SiC, Al_2O_3, TiC, Si_3N_4, graphite, mica, glass, slag, magnesium oxide, and boron carbide have been incorporated into vigorously agitated partially solidified aluminum alloy slurries by this technique.

Liquid-Metal Infiltration. The Primex pressureless metal infiltration process is based on material and process controls that allow a metal to infiltrate substantially nonreactive reinforcements without the application of pressure or vacuum. Reinforcement level can be controlled by the starting density of the material being infiltrated. As long as interconnected porosity and appropriate infiltration conditions exist, the liquid metal will spontaneously infiltrate into the preform.

Key process ingredients for the manufacture of reinforced aluminum composites include the aluminum alloy, a nitrogen atmosphere, and magnesium present in the system. During heating to infiltration temperature (~750 °C, or 1380 °F), the magnesium reacts with the nitrogen atmosphere to form magnesium nitride (Mg_3N_2). The Mg_3N_2 is the infiltration enhancer that allows the aluminum alloy to infiltrate the reinforcing phase without the necessity of applied pressure or vacuum. During infiltration the Mg_3N_2 is reduced by the aluminum to form a small amount of aluminum nitride (AlN). The AlN is found as small precipitates and as a thin film on the surface of the reinforcing phase. Magnesium is released into the alloy by this reaction.

The pressureless infiltration process can produce a wide array of engineered composites by tailoring of alloy chemistry, particle type, shape, size, and loading. Particulate loading in cast composites can be as high as 75 vol%, given the right combination of particle shape and size. Figure 4 shows a typical microstructure.

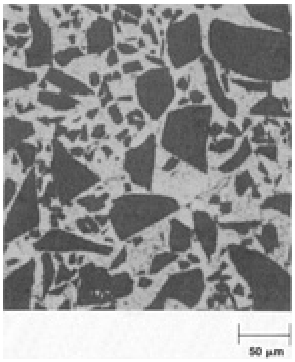

Fig. 4 Discontinuous Al/SiC MMC (60 vol% SiC) produced by the liquid-metal infiltration process

The most widely used cast composite produced by liquid-metal infiltration is an Al-10Si-1Mg alloy reinforced with 30 vol% SiC. The 1% Mg present in this alloy is obtained during infiltration by the reduction of the Mg_3N_2. This composite system is being used for all casting processes except die casting. The composite most used for die casting is based on this system, with the addition of 1% Fe. Alloy modifications can be made to the alloy prior to infiltration or in the crucible prior to casting. The only universal alloy restriction for this composite system is the presence of magnesium to allow the formation of the Mg_3N_2. For the SiC-containing systems, silicon must also be present in sufficient quantity to suppress the formation of aluminum carbide (Al_4C_3). Composites consisting of Al_2O_3-reinforced aluminum that exhibit low excessive wear rates are also produced.

An important application area for pressureless molten metal infiltration is Al/SiC_p packages, substrates, and support structures for electronic components. Typical requirements include a low coefficient of thermal expansion (CTE) to reduce mechanical stresses imposed on the electronic device during attachment and operation, high thermal conductivity for heat dissipation, high stiffness to minimize distortion, and low density for minimum weight. Compared with conventional aluminum alloys, composites having high loadings of SiC particles feature greatly reduced CTEs and significantly higher elastic moduli, with little or no penalty in thermal conductivity or density (Table 5).

Table 5 Physical properties of an Al/SiC/*xx*p MMC for electronic applications

Property	Composite, SiC loading		Typical aluminum alloys
	55 vol%	**70 vol%**	
Coefficient of thermal expansion, 10^{-6}/°C (10^{-6}/°F)	8.5 (4.7)	6.2 (3.4)	22-24 (12-13)
Thermal conductivity, W/m · K (Btu/h · ft · °F)	160 (93)	170 (99)	150-180 (87-104)
Density, g/cm^3 (lb/in.^{3})	2.95 (0.106)	3.0 (0.0108)	2.7 (0.097)
Elastic modulus, GPa (10^6 psi)	200 (29)	270 (39)	70 (10)

Spray deposition involves atomizing a melt and, rather than allowing the droplets to solidify totally as for metal powder manufacture, collecting the semi-solid droplets on a substrate. The process is a hybrid rapid solidification process because the metal experiences a rapid transition through the liquidus to the solidus, followed by slow cooling from the solidus to room temperature. This results in a refined grain and precipitation structure with no significant increase in solute solubility.

The production of MMC ingot by spray deposition can be accomplished by introducing particulate into the standard spray deposition metal spray leading to codeposition with the atomized metal onto the substrate. Careful control of the atomizing and particulate feeding conditions is required to ensure that a uniform distribution of particulate is produced within a typically 95 to 98% dense aluminum matrix.

A number of aluminum alloys containing SiC particulate have been produced by spray deposition. These include aluminum-silicon casting alloys and the 2*xxx*, 6*xxx*, 7*xxx*, and 8*xxx* (aluminum-lithium) series wrought alloys. Significant increases in specific modulus have been realized with SiC-reinforced 8090 alloy (Table 6). Products that have been produced by spray deposition include solid and hollow extrusions, forgings, sheet, and remelted pressure die castings.

Table 6 Properties of conventionally processed aluminum alloys (ingot metallurgy) and spray-deposited aluminum MMCs

Material	Elastic modulus		Density		Specific modulus	Improvement, %
	GPa	**10^6 psi**	**g/cm^3**	**lb/in.^{3}**		
2014	72	10	2.8	0.101	25.7	0
8090	80	12	2.55	0.092	31.4	22
2014/SiC/15p$^{(a)}$	95	14	2.84	0.103	33.5	30

(a) Spray codeposited, extruded, and peak aged

P/M Aluminum MMCs. Powder metallurgy processing of aluminum MMCs involves both SiC particulates and whiskers, although Al_2O_3 particles and Si_3N_4 whiskers have also been employed. Processing involves (1) blending of the gas-atomized matrix alloy and reinforcement in powder form; (2) compacting (cold pressing) the homogeneous blend to roughly 80% density; (3) degassing the preform (which has an open interconnected pore structure) to remove volatile contaminants (lubricants and mixing and blending additives), water vapor, and gases; and (4) consolidation by vacuum hot pressing or hot isostatic pressing. The hot-pressed cylindrical billets can be subsequently extruded, rolled, or forged. Whisker-reinforced aluminum MMCs may experience some whisker alignment during extrusion or rolling (Fig. 5). Control of whisker alignment enables production of aluminum MMC product forms with directional properties needed for some high-performance applications. Cross rolling of sheet establishes a more planar whisker alignment, producing a two-dimensional isotropy.

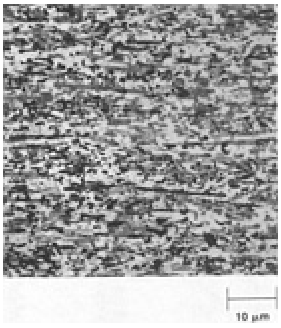

Fig. 5 SiC whisker-reinforced (20 vol% SiC) aluminum alloy sheet with the whiskers aligned in the direction of rolling

The mechanical properties of whisker-reinforced aluminum MMCs are superior to particle-reinforced composites at any common volume fraction (Fig. 6). Tables 7 and 8 show the effects of whisker alignment on the properties of aluminum MMCs. Table 9 lists typical mechanical properties for particle-reinforced aluminum alloys.

Table 7 Typical properties of MMC billet and extruded plate having density of 2.86 g/cm^3 (0.103 lb/in.^{3}) to show the effects of SiC whisker alignment

MMC material form	Test specimen orientation	Ultimate tensile		Yield strength(a)		Coefficient of thermal expansion (α)	
		MPa	**ksi**	**MPa**	**ksi**	**10^{-6}/K**	**10^{-6}/°F**
305 mm (12 in.) diam cylindrical billet	Longitudinal (axial)	496	71.9	351	50.9	16.1	8.95
	Transverse	503	72.9	358	51.9	16.4	9.12
13 by 125 mm ($\frac{1}{2}$ by 5 in.) extrusion	Longitudinal	737	107	448	64.9	13.0	7.23
	Transverse (long)	462	67.0	379	54.9	19.6	10.9

(a) 0.2% offset

Table 8 Typical properties of SiC whisker-reinforced aluminum alloy sheet

Sheet thickness		Test specimen orientation	Ultimate tensile strength		Yield strength(a)		Elongation (*e*), %	Young's, modulus, *E*		Fracture toughness, K_c	
mm	**in.**		**MPa**	**ksi**	**MPa**	**ksi**		**GPa**	**10^6 psi**	**MPa$\sqrt{m}$**	**ksi$\sqrt{in.}$**
2.54	0.100	Longitudinal (along roll direction)	718	104	573	83.1	5.3	114	16.5	55	50
2.54	0.100	Transverse (90° to roll direction)	559	81.0	386	56.4	8.5	95	14	59	54

Material: 2124-T6 reinforced with 15 vol% SiC whiskers.

(a) 0.2% offset

Table 9 Typical mechanical properties of SiC particulate-reinforced aluminum alloy composites

Alloy and vol %	Modulus of elasticity		Yield strength		Ultimate tensile strength		Ductility, %
	GPa	**10^6 psi**	**MPa**	**ksi**	**MPa**	**ksi**	
6061							
Wrought	68.9	10	275.8	40	310.3	45	12
15	96.5	14	400.0	58	455.1	66	7.5

20	103.4	15	413.7	60	496.4	72	5.5
25	113.8	16.5	427.5	62	517.1	75	4.5
30	120.7	17.5	434.3	63	551.6	80	3.0
35	134.5	19.5	455.1	66	551.6	80	2.7
40	144.8	21	448.2	65	586.1	85	2.0
2124							
Wrought	71.0	10.3	420.6	61	455.1	66	9
20	103.4	15	400.0	58	551.6	80	7.0
25	113.8	16.5	413.7	60	565.4	82	5.6
30	120.7	17.5	441.3	64	593.0	86	4.5
40	151.7	22	517.1	75	689.5	100	1.1
7090							
Wrought	72.4	10.5	586.1	85	634.3	92	8
20	103.4	15	655.0	95	724.0	105	2.5
25	115.1	16.7	675.7	98	792.9	115	2.0
30	127.6	18.5	703.3	102	772.2	112	1.2
35	131.0	19	710.2	103	724.0	105	0.90
40	144.8	21	689.5	100	710.2	103	0.90
7091							
Wrought	72.4	10.5	537.8	78	586.1	85	10
15	96.5	14	579.2	84	689.5	100	5.0
20	103.4	15	620.6	90	724.0	105	4.5
25	113.8	16.5	620.6	90	724.0	105	3.0
30	127.6	18.5	675.7	98	765.3	111	2.0
40	139.3	20.2	620.6	90	655.0	95	1.2

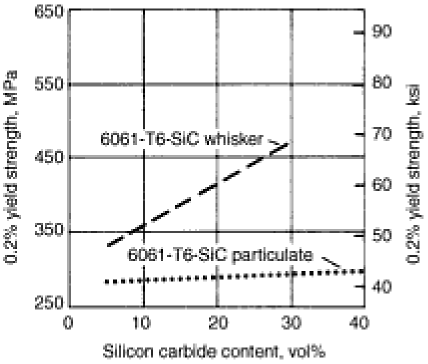

Fig. 6 Yield strength comparison between whisker- and particulate-reinforced aluminum MMCs

Continuous Fiber Aluminum MMCs

As shown in Fig. 1, aluminum MMCs reinforced with continuous fibers provide the highest performance/strength. Because of their high cost, however, most applications have been limited to the aerospace industry.

Aluminum/boron is a technologically mature continuous fiber MMC (Fig. 7). Applications for this composite include tubular truss members in the midfuselage structure of the Space Shuttle orbiter and cold plates in electronic microchip carrier multilayer boards. Fabrication processes for aluminum/boron composites are based on hot-press diffusion bonding of alternating layers of aluminum foil and boron fiber mats (foil-fiber-foil processing) or plasma spraying methods. Selected properties of aluminum/boron composites are given in Table 10.

Table 10 Room-temperature properties of unidirectional continuous-fiber, aluminum-matrix composites

Property	B/6061 Al	SCS-2/6061 Al(a)	P100 Gr/6061 Al	FP/Al-2Li(b)
Fiber content, vol%	48	47	43.5	55
Longitudinal modulus, GPa (10^6 psi)	214 (31)	204 (29.6)	301 (43.6)	207 (30)
Transverse modulus, GPa (10^6 psi)	. . .	118 (17.1)	48 (7.0)	144 (20.9)
Longitudinal strength, MPa (ksi)	1520 (220)	1462 (212)	543 (79)	552 (80)
Transverse strength, MPa (ksi)	. . .	86 (12.5)	13 (2)	172 (25)

(a) SCS-2 is a silicon carbide fiber.

(b) FP is an alpha alumina (α-Al_2O_3) fiber

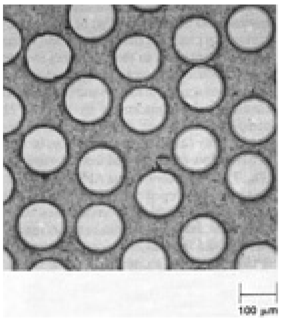

Fig. 7 Cross section of a continuous-fiber-reinforced aluminum/boron composite. Shown here are 142 μm diam boron filaments coated with B_4C in a 6061 aluminum alloy matrix

Continuous SiC fibers are often used as replacements for boron fibers because they have similar properties (e.g., a tensile modulus of 400 GPa, or 60 × 10^6 psi) and offer a cost advantage. One such SiC fiber is SCS, which can be manufactured with any of several surface chemistries to enhance bonding with a particular matrix, such as aluminum or titanium. The SCS-2 fiber, tailored for aluminum, has a 1 μm (0.04 mil) thick carbon rich coating that increases in silicon content toward its outer surface.

Hot molding is a low-pressure, hot-pressing process designed to fabricate Al/SiC parts at significantly lower cost than is possible with a diffusion-bonding/solid-state process. Because the SCS-2 fibers can withstand molten aluminum for long periods, the molding temperature can be raised into the liquid-plus-solid region of the alloy to ensure aluminum flow and consolidation at low pressure, thereby eliminating the need for high-pressure die molding equipment.

The hot-molding process is analogous to the autoclave molding of graphite-epoxy, in which components are molded in an open-faced tool. The mold in this case is a self-heating, slip-cast ceramic tool that contains the profile of the finished part. A plasma-sprayed aluminum preform is laid into the mold, heated to near molten aluminum temperature, and pressure-consolidated in an autoclave by a metallic vacuum bag.

Aluminum/SiC MMCs exhibit increased strength and stiffness as compared with unreinforced aluminum, with no weight penalty. Tensile properties of 6061/SCS-2 composites are given in Table 10. In contrast to the base metal, the composite retains its room-temperature tensile strength at temperatures up to 260 °C (500 °F).

Aluminum/graphite MMC development was initially prompted by the commercial appearance of strong and stiff carbon fibers in the 1960s. Carbon fibers offer a range of properties, including an elastic modulus up to 966 GPa (140 psi × 10^6) and a negative CTE down to -1.62 × 10^{-6}/°C (-0.9 × 10^{-6}/°F). However, carbon and aluminum in combination are difficult materials to process into a composite. A deleterious reaction between carbon and aluminum, poor wetting of carbon by molten aluminum, and oxidation of the carbon are significant technical barriers to the production of these composites. Two processes are currently used for making commercial aluminum MMCs: liquid metal infiltration of the matrix on spread tows and hot press bonding of spread tows sandwiched between sheets of aluminum. With both precursor wires and metal-coated fibers, secondary processing such as diffusion bonding or pultrusion is needed to make structural elements. Squeeze casting also is feasible for the fabrication of this composite.

Precision aerospace structures with strict tolerances on dimensional stability need stiff, lightweight materials that exhibit low thermal distortion. Aluminum/graphite MMCs have the potential to meet these requirements, Unidirectional P100 Gr/6061 aluminum pultruded tube exhibits an elastic modulus in the fiber direction significantly greater than that of steel, and it has a density approximately one-third that of steel. Properties are listed in Table 10.

Aluminum/Al_2O_3 MMCs can be fabricated by a number of methods, but liquid or semi-solid-state processing techniques are commonly used. Aluminum oxide fibers, which include Fiber FP (99.5% Al_2O_3) and Saffil ($96Al_2O_3$-$4SiO_2$) are inexpensive and provide the composite with improved properties as compared with those of unreinforced aluminum alloys. For example, the composite has an improved resistance to wear and thermal fatigue deformation and a reduced CTE. Continuous fiber Al/Al_2O_3 MMCs are fabricated by arranging Al_2O_3 tapes in a desired orientation to make a preform, inserting the preform into a mold, and infiltrating the preform with molten aluminum via a vacuum assist. Reinforcement-to-matrix bonding is achieved by small additions of lithium to the melt. Table 10 gives the room-temperature properties of a unidirectional $Al\text{-}2Li/Al_2O_3$.

Titanium-Matrix Composites

Titanium is selected as a matrix metal because of its good specific strength at both room and moderately elevated temperature and its excellent corrosion resistance. Because titanium retains its strength at higher temperatures than aluminum, it has increasingly been used as a replacement for aluminum in aircraft and missile structures as the operating speeds of these items have increased from subsonic to supersonic.

Continuous Fiber Titanium MMCs. Silicon carbide fibers are the reinforcement of choice for titanium MMCs. The SCS-6 fiber is a carbon-cored monofilament that is 142 μm in diameter. A tungsten-cored fiber that has a carbon coating has also been developed with a diameter of 127 μm. A tungsten-cored monofilament with carbon and titanium diboride coatings that is 102 μm in diameter is also available. Fiber contents of 30 to 40 vol% are common (Fig. 8). Conventional matrix alloys include Ti-6Al-4V for low-temperature applications and Ti-6Al-2Sn-4Zr-2Mo (Ti-6242) when higher creep resistance is required or when the temperature is higher than the maximum use temperature for Ti-6Al-4V. The Ti-6242 alloy is used in turbine engine actuator pistons and reinforced fan frames. More recently, titanium aluminide ordered intermetallics such as Ti-22Al-23Nb and Ti-22Al-26Nb have been used as matrix materials. These materials are being developed for rotating blades and impellers. Processing techniques for titanium MMCs used for aerospace applications include fiber-foil-fiber processing and tape casting or wire winding used in conjunction with hot isostatic pressing. Plasma spraying has also been employed to deposit a titanium matrix onto the fibers. Similarly, electron beam physical vapor deposition of metal on fiber has also been demonstrated. Table 11 gives properties for a representative unidirectional SiC/Ti laminate.

Table 11 Room-temperature properties of a unidirectional SiC_c/Ti MMC

Property	SCS-6/Ti-6Al-4V
Fiber content, vol%	37
Longitudinal modulus, GPa (10^6 psi)	221 (32)
Transverse modulus, GPa (10^6 psi)	165 (24)
Longitudinal strength, MPa (ksi)	1447 (210)
Transverse strength, MPa (ksi)	413 (60)

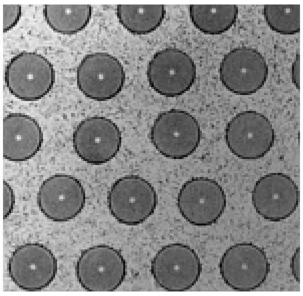

Fig. 8 Typical fiber array in a SiC-reinforced titanium MMC. Actual fiber diameters are 127 μm. Courtesy of Charles R. Rowe, Atlantic Research Corporation

Particle-Reinforced Titanium MMCs are processed by P/M methods. Although a variety of materials have been studied, the most common combination is Ti-6Al-4V reinforced with 10 to 20 wt% TiC. These composites offer increased hardness and wear resistance over conventional titanium alloys. Properties of unreinforced and reinforced Ti-6Al-4V are compared in Table 12.

Table 12 Properties of TiC particle-reinforced titanium MMCs

Property	Ti-6Al-4V	10 wt% TiC/Ti-6Al-4V	20 wt% TiC/Ti-6Al-4V
Density, g/cm^3 (lb/in.^{3})	4.43 (0.160)	4.45 (0.16)	4.52 (0.162)
Tensile strength, MPa (ksi), at:			
RT	896 (130)	999 (145)	1055 (153)
540 °C (1000 °F)	448 (65)	551 (80)	620 (90)
Modulus, GPa (10^6 psi), at:			
RT	113 (16.5)	133 (19.3)	144 (21)
540 °C (1000 °F)	89 (13)	105 (15.3)	110 (16)
Fatigue limit (10^6 cycles), MPa (ksi)	517 (75)	275 (40)	. . .
Fracture toughness, MPa$\sqrt{m}$ (ksi$\sqrt{in.}$)	55 (50)	44 (40)	32 (29)
Coefficient of linear thermal expansion (RT to 540 °C, or 1000 °F), ppm/°C	8.5	8.1	8.0
Hardness, HRC	34	40	44

RT, room temperature

Other MMCs of Importance

Magnesium-matrix composites are being developed to exploit essentially the same properties as those provided by aluminum MMCs: high stiffness, light weight, and low CTE. In practice, the choice between aluminum and magnesium as a matrix is usually made on the basis of weight versus corrosion resistance. Magnesium is approximately two-thirds as dense as aluminum, but it is more active in a corrosive environment. Magnesium has a lower thermal conductivity, which is sometimes a factor in its selection. Magnesium MMCs include continuous fiber Gr/Mg for space structures, short staple fiber Al_2O_3/Mg for automotive engine components, and discontinuous SiC or B_4C/Mg for engine components and low-expansion electronic packaging materials. Matrix alloys include AZ31, AZ91, ZE41, QE22, and EZ33. Processing methods parallel those used for the aluminum MMC counterparts.

Copper-matrix composites have been produced with continuous tungsten, silicon carbide, and graphite fiber reinforcements. Of the three composites, continuous graphite/copper MMCs have been studied the most.

Interest in continuous graphite/copper MMCs gained impetus from the development of advanced graphite fibers. Copper has good thermal conductivity, but it is heavy and has poor elevated-temperature mechanical properties. Pitch-base graphite fibers have been developed that have room-temperature axial thermal conductivity properties better than those of copper. The addition of these fibers to copper reduces density, increases stiffness, raises the service temperature, and provides a mechanism for tailoring the coefficient of thermal expansion. One approach to the fabrication of graphite/copper MMCs uses a plating process to envelop each graphite fiber with a pure copper coating, yielding MMC fibers flexible enough to be woven into fabric. The copper-coated fibers must be hot pressed to produce a consolidated component. Table 13 compares the thermal properties of aluminum and copper MMCs with those of unreinforced aluminum and copper. Graphite/copper MMCs have the potential to be used for thermal management of electronic components, satellite radiator panels, and advanced airplane structures.

Table 13 Thermal properties of unreinforced and reinforced aluminum and copper

Material	Reinforcement content, vol%	Density		Axial thermal conductivity		Axial coefficient of thermal expansion	
		g/cm^3	lb/ft^3	W/m · °C	Btu/ft · h · °F	10^{-6}/°C	10^{-6}/°F
Aluminum	0	2.71	169	221	128	23.6	13.1
Copper	0	8.94	558	391	226	17.6	9.7
SiC_p/Al	40	2.91	182	128	74	12.6	7
P120 Gr/Al	60	2.41	150	419	242	-0.32	-0.17
P120 Gr/Cu	60	4.90	306	522	302	-0.07	-0.04

Superalloy-Matrix Composites. In spite of their poor oxidation resistance and high density, refractory metal (tungsten, molybdenum, and niobium) wires have received a great deal of attention as fiber reinforcement materials for use in high-temperature superalloy MMCs. Although the theoretical specific strength potential of refractory alloy fiber-reinforced composites is less than that of ceramic fiber-reinforced composites, the more ductile metal fiber systems are more tolerant of fiber-matrix reactions and thermal expansion mismatches. When refractory metal fibers are used to reinforce a ductile and oxidation-resistant matrix, they are protected from oxidation, and the specific strength of the composite is much higher than that of superalloys at elevated temperatures.

Fabrication of superalloy MMCs is accomplished via solid-phase, liquid-phase, or deposition processing. The methods include investment casting, the use of matrix metals in thin sheet form, the use of matrix metals in powder sheet form made by rolling powders with an organic binder, powder metallurgy techniques, slip casting of metal alloy powders, and arc spraying.

Figure 9 compares the elevated-temperature tensile strength of a nickel-base superalloy (Waspaloy) reinforced with various refractory wires. As this figure indicates, a composite consisting of 50 vol% W-24Re-HfC had the highest strength at 1093 °C (2000 °F).

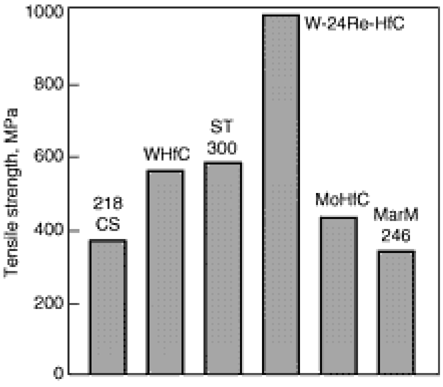

Fig. 9 Elevated temperature (1093 °C, or 2000 °F) tensile strength of Waspaloy reinforced with 50 vol% refractory metal wire. 218 CS represents potassium-doped tungsten. ST 300 is a W-1.0ThO$_2$ alloy. Comparative data are included for unreinforced MarM 246, a nickel-base superalloy.

Intermetallic-Matrix Composites. One disadvantage of superalloy MMCs is their high density, which limits the potential minimum weight of parts made from these materials. High melting points and relatively low densities make intermetallic-matrix composites (IMCs) viable candidates for lighter turbine engine materials. Aluminides of nickel, titanium, and iron have received the most attention as matrices for IMCs. Property data on TiB$_2$-reinforced titanium aluminides can be found in the article "Structural Intermetallics" in this Section.

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Structural Intermetallics

Introduction

ALLOYS based on ordered intermetallic compounds constitute a unique class of metallic material that form long-range ordered crystal structures (Fig. 1) below a critical temperature, generally referred to as the critical ordering temperature (T_c). These ordered intermetallics usually exist in relatively narrow compositional ranges around simple stoichiometric ratio (see the phase diagrams shown in this article).

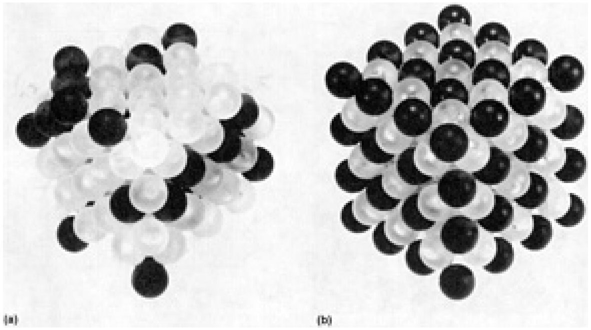

Fig. 1 Atomic arrangements of conventional alloys and ordered intermetallic compounds. (a) Disordered crystal structure of a conventional alloy. (b) Long-range ordered crystal structure of an ordered intermetallic compound

The search for new high-temperature structural materials has stimulated much interest in ordered intermetallics. Recent interest has been focused on nickel aluminides based on Ni_3Al and NiAl, iron aluminides based on Fe_3Al and FeAl, and titanium aluminides based on Ti_3Al and TiAl. These aluminides possess many attributes that make them attractive for high-temperature structural applications. They contain enough aluminum to form, in oxidizing environments, thin films of alumina (Al_2O_3) that are compact and protective. They have low densities, relatively high melting points, and good high-temperature strength properties (Tables 1 and 2).

Table 1 Properties of nickel, iron, and titanium aluminides

Alloy	Crystal structure[(a)]	Critical ordering temperature (T_c)		Melting point (T_m)		Material density, g/cm^3	Young's modulus	
		°C	**°F**	**°C**	**°F**		**GPa**	**10^6 psi**
Ni_3Al	$L1_2$ (ordered fcc)	1390	2535	1390	2535	7.50	179	25.9
NiAl	*B*2 (ordered bcc)	1640	2985	1640	2985	5.86	294	42.7
Fe_3Al	$D0_3$ (ordered bcc)	540	1000	1540	2805	6.72	141	20.4

	*B*2 (ordered bcc)	760	1400	1540	2805	. . .	. . .	. . .
FeAl	*B*2 (ordered bcc)	1250	2280	1250	2280	5.56	261	37.8
Ti_3Al	$D0_{19}$ (ordered hcp)	1100	2010	1600	2910	4.2	145	21.0
TiAl	$L1_0$ (ordered tetragonal)	1460	2660	1460	2660	3.91	176	25.5
$TiAl_3$	$D0_{22}$ (ordered tetragonal)	1350	2460	1350	2460	3.4	. . .	. . .

(a) fcc, face-centered cubic; bcc, body-centered cubic; hcp, hexagonal close packed

Table 2 Attributes and upper use temperature limits for nickel, iron, and titanium aluminides

Alloy	Attributes	Maximum use temperature, °C (°F)	
		Strength limit	**Corrosion limit**
Ni_3Al	Oxidation, carburization, and nitridation resistance; high-temperature strength	1000 (1830)	1150 (2100)
NiAl	High melting point; high thermal conductivity; oxidation, carburization, and nitridation resistance	1200 (2190)	1400 (2550)
Fe_3Al	Oxidation and sulfidation resistance	600 (1110)	1100 (2010)
FeAl	Oxidation, sulfidation, molten salt, and carburization resistance	800 (1470)	1200 (2190)
Ti_3Al	Low density; good specific strength	760 (1400)	650 (1200)

Nickel, iron, and titanium aluminides, like other ordered intermetallics, exhibit brittle fracture and low ductility at ambient temperatures. It has also been found that quite a number of ordered intermetallics, such as iron aluminides, exhibit environmental embrittlement at ambient temperatures. The embrittlement involves the reaction of water vapor in air with reactive elements (aluminum, for example) in intermetallics to form atomic hydrogen, which drives into the metal and causes premature fracture. Thus, the poor fracture resistance and limited fabricability have restricted the use of aluminides as engineering materials in most cases. However, in recent years, alloying and processing have been employed to overcome the brittleness problem of ordered intermetallics. Success in this work has inspired parallel efforts aimed at improving strength properties. The results have led to the development of a number of attractive intermetallic alloys having useful ductility and strength.

Figure 2 illustrates the crystal structures showing the ordered arrangements of atoms in several of these aluminides. For most of the aluminides listed in Table 1, the critical ordering temperature is equal to the melting temperature. Others disorder at somewhat lower temperatures, and Fe_3Al passes through two ordered structures ($D0_3$ and *B*2) before becoming disordered. Many of the aluminides exist over a range of compositions, but the degree of order decreases as the deviation from stoichiometry increases, Additional elements can be incorporated without losing the ordered structure. For example, in Ni_3Al, silicon atoms are located in aluminum sites, cobalt atoms on nickel sites, and iron atoms on either. In many instances, the so-called intermetallic compounds can be used as bases for alloy development to improve or optimize properties for specific applications.

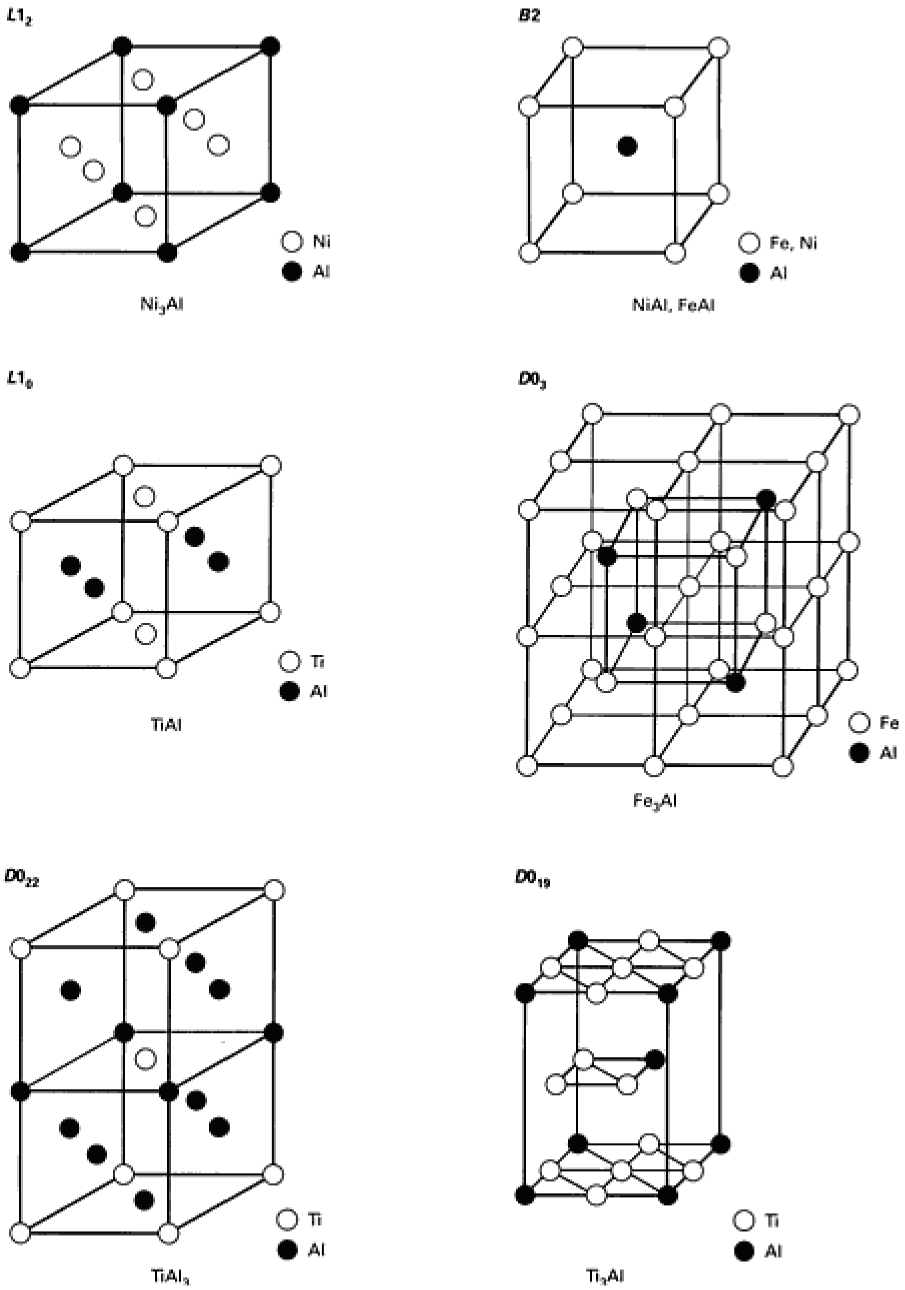
L1₂
Ni
Al
Ni₃Al
B2
Fe, Ni
Al
NiAl, FeAl
L1₀
Ti
Al
TiAl
D0₃
Fe
Al
Fe₃Al
D0₂₂
Ti
Al
TiAl₃
D0₁₉
Ti
Al
Ti₃Al

Fig. 2 Crystal structures of nickel, iron, and titanium aluminides

Nickel Aluminides

The nickel-aluminum phase diagram shows two stable intermetallic compounds, Ni_3Al and NiAl, formed on the nickel-rich end (Fig. 3). The compound Ni_3Al has an $L1_2$ crystal structure, a derivative of the face-centered cubic (fcc) crystal structure; NiAl has a *B*2 structure, a derivative of the body-centered cubic (bcc) crystal structure (see Fig. 2). Because of the different crystal structures, the two nickel aluminides have quite different physical and mechanical properties.

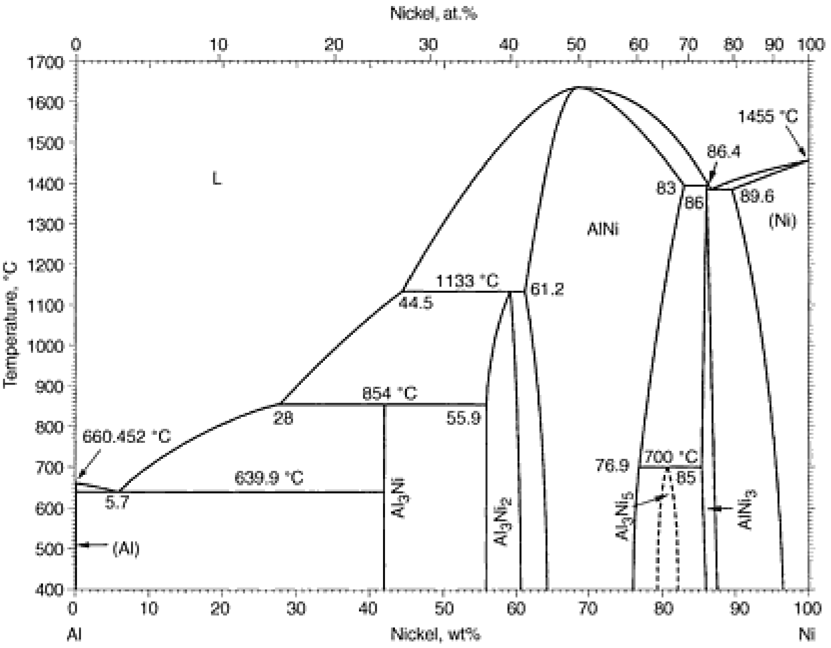

Fig. 3 The nickel-aluminum phase diagram showing both NiAl and Ni_3Al compounds on the nickel-rich end

Ni_3Al Aluminides

The aluminide Ni_3Al is of interest because of its excellent strength and oxidation resistance at elevated temperatures (see Table 2). This intermetallic has long been used as a strengthening constituent in high-temperature, nickel-base superalloys, which owe their outstanding strength properties to a fine dispersion of precipitation particles of the ordered γ' phase (Ni_3Al) embedded in a ductile disordered matrix. (See the Section "Superalloys" in this Handbook).

Single crystals of Ni_3Al are ductile at ambient temperatures, but polycrystalline Ni_3Al fails by brittle grain-boundary fracture with very little plasticity. This effect persists even in very high-purity materials where no grain-boundary segregation of impurities can be detected. The observation of this characteristic turned attention toward a search for segregants that might act in a beneficial way.

Studies of segregants led to the discovery that small (~0.1 wt%) boron additions not only eliminated the brittle behavior of Ni_3Al but converted the material to a highly malleable form exhibiting tensile ductility as high as 50% at room temperature. The beneficial effect of boron is, however, dependent on stoichiometry, and boron is effective in increasing the ductility of Ni_3Al only in alloys containing less than 25 at.% aluminum. Since gaining the knowledge that microalloying with boron can ductilize polycrystalline Ni_3Al, a number of Ni_3Al alloy compositions have been developed. As shown in Table 3, macroalloying additions include chromium, iron, zirconium, and molybdenum. These alloying additions were made to improve strength, castability, hot workability, and corrosion resistance. The effects of these alloying additions are described in the following paragraphs.

Table 3 Nominal compositions of selected Ni_3Al alloys

Alloy[a]	Composition, wt%						
	Al	**Cr**	**Fe**	**Zr**	**Mo**	**B**	**Ni**
IC-50	11.3	. . .	. . .	0.6	. . .	0.02	bal
IC-74M	12.4	. . .	. . .	. . .	. . .	0.05	bal
IC-218	8.5	7.8	. . .	0.8	. . .	0.02	bal
IC-218 LZr	8.7	8.1	. . .	0.2	. . .	0.02	bal
IC-221	8.5	7.8	. . .	1.7	. . .	0.02	bal
IC-357	9.5	7.0	11.2	0.4	1.3	0.02	bal
IC-396M	8.0	7.7	. . .	0.8	3.0	0.01	bal

(a) Designations used by Oak Ridge National

Laboratory, Oak Ridge,TN

Anomalous Dependence of Yield Strength on Temperature. Ni_3Al is one of a number of intermetallic alloys that exhibit an engineering yield strength (0.2% offset) that increases with increasing temperature. This is shown in Fig. 4, which is a plot of yield stress as a function of test temperature. The anomalous yielding effect, which is lower at lower strains, occurs because of the extremely rapid work hardening. The anomalous yielding behavior makes Ni_3Al stronger than many commercial solid-solution alloys (such as type 316 stainless steel and Hastelloy alloy X) at elevated temperatures (Fig. 4).

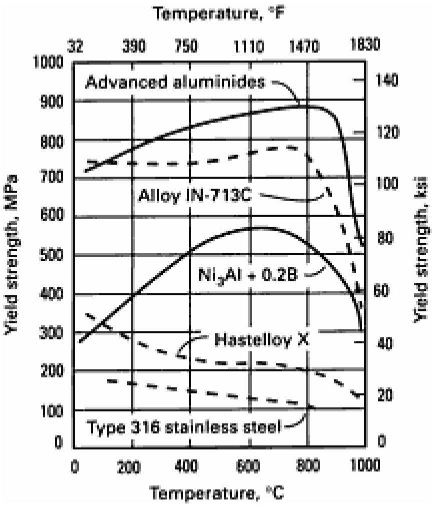

Fig. 4 Yield strength versus test temperature for Ni_3Al alloys, two superalloys, and type 316 stainless steel

As with boron-doped Ni_3Al, Ni_3Al alloys (Table 3) also exhibit rising yield strength with rising temperature. Figure 5 shows that the yield strength of four nickel aluminide alloys tends to rise to a maximum in the temperature range of ~400 to 650 °C (~750 to 1200 °F). Above this temperature range, the yield strength declines.

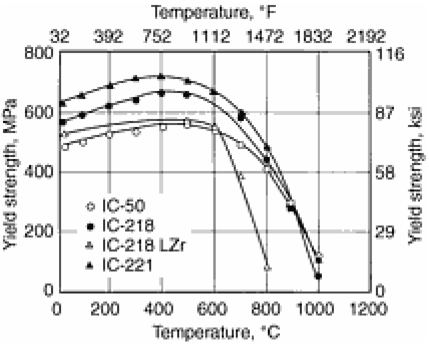

Fig. 5 Variation of yield strength with test temperature for selected nickel aluminide alloys. Strain rate, 0.5 mm/mm per min. See Table 3 for alloy compositions.

Mechanical Properties. The study of ductility and strength of Ni_3Al has led to the development of ductile nickel aluminide alloys for structural applications with the following composition range (in atomic percent):

Ni-(14-18)Al-(6-9)Cr-(1-4)Mo-(0.01-1.5)Zr/Hf-(0.01-0.20)B

In these aluminide alloys, 6 to 9 at.% Cr is added to reduce environmental embrittlement in oxidizing environments at elevated temperatures. Zirconium and hafnium additions most effectively improve high-temperature strength via solid-solution hardening effects. Molybdenum additions improve strength at ambient and elevated temperatures. Microalloying with boron reduces moisture-induced hydrogen embrittlement and enhances grain-boundary cohesive strength, resulting in sharply increased ductility at ambient temperatures. In some cases, certain amounts (<20 at.%) of cobalt and iron are added to replace nickel, and aluminum and nickel, respectively, in order to further improve hardness and corrosion resistance. The alloys with optimum properties usually contain 5 to 15 vol% of the disordered γphase, which has the beneficial effect of reducing environmental embrittlement in oxidizing atmospheres and improving creep properties at elevated temperatures.

Figure 6 compares the tensile properties of cast Ni_3Al alloys with cast HU alloy (Fe-20Cr-39Ni-2.5Si). It is clear from this figure that the Ni_3Al alloys are nearly twice as strong at room temperature and six times as strong at 1000 °C (1830 °F). The tensile properties of high-aluminum (4.5 wt% Al) alloy 214 and cast and powder metallurgy (P/M) processed Ni_3Al alloys are compared in Fig. 7. The P/M processed IC-221 alloy in Fig. 7 is significantly stronger than alloy 214 or the cast Ni_3Al-based alloys.

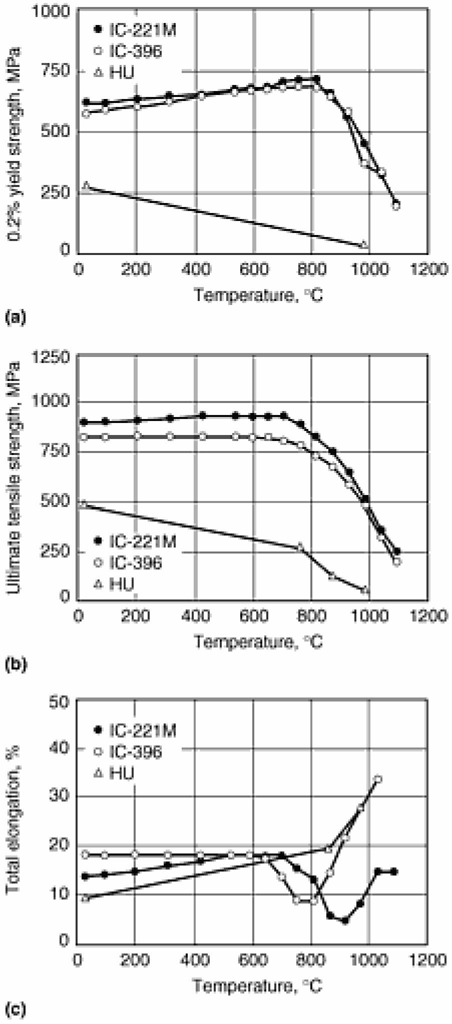

Fig. 6 Comparison of tensile properties of cast Ni_3Al alloys with cast HU alloy. (a) 0.2% yield strength. (b) Ultimate tensile strength. (c) Total elongation

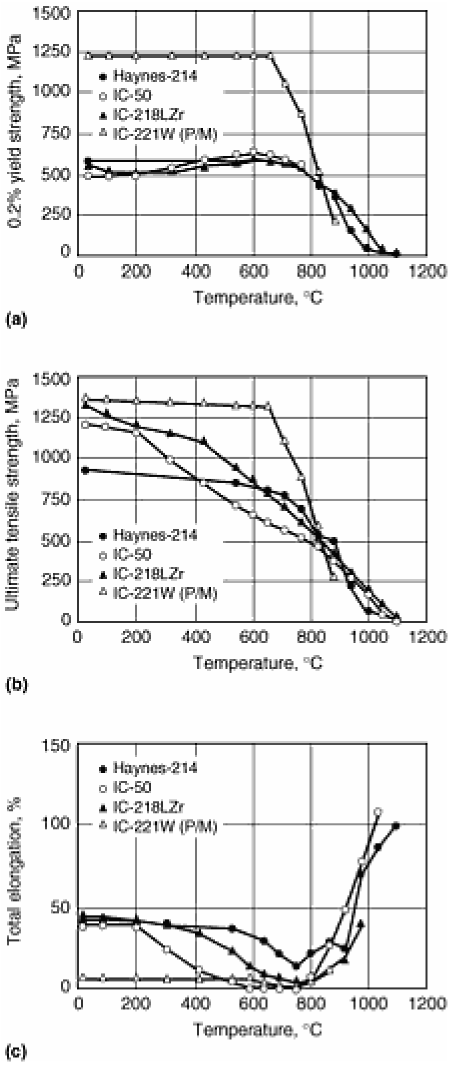

Fig. 7 Comparison of tensile properties of cast and P/M Ni_3Al Alloys with Haynes 214. (a) 0.2% yield strength. (b) Ultimate tensile strength. (c) Total elongation

Creep properties of Ni_3Al alloys have been characterized as functions of stress, temperature, and composition. Hafnium and zirconium additions are most effective in improving the resistance of Ni_3Al. Figure 8 shows creep data for the polycrystalline nickel aluminide alloy IC-221. The creep properties of Ni_3Al alloys, like those of nickel-base superalloys, are sensitive to grain size, but the Ni_3Al alloys have better creep resistance for coarse-grain materials (e.g., cast materials). For applications where creep resistance is important, coarse-grain material is more desirable at temperatures greater than 700 °C (1290 °F). Creep properties of single-crystal Ni_3Al alloys containing refractory elements such as tantalum have been studied at temperatures up to 1000 °C (1830 °F). In general, the creep resistance of Ni_3Al is comparable to that of most of the nickel-base superalloys, but it is not as good as that of some advanced single-crystal, nickel-base superalloys used for jet engine turbine blades.

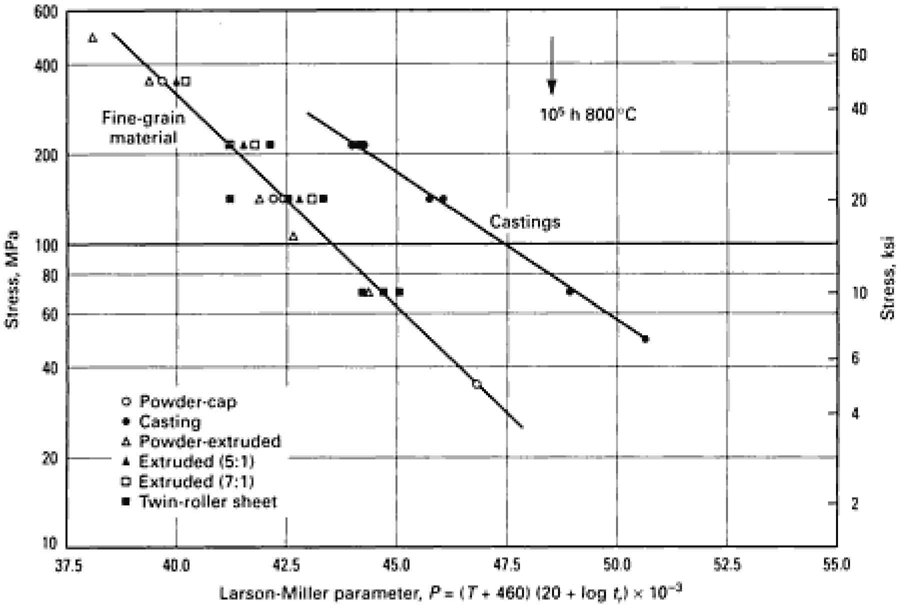

Fig. 8 Larson-Miller parameter (*P*) plot showing the effect of processing on the creep-rupture properties of IC-221. Tests were conducted in the temperature range of 650 to 870 °C (1200 to 1600 °F) for times ranging from 10 to 12,464 h.

Fatigue and fatigue crack growth are substantially better in Ni_3Al alloys than in nickel-base superalloys in tests below the range of the ductility minimum; see Fig. 9 for room-temperature fatigue crack growth. The good fatigue resistance of Ni_3Al and other ordered intermetallic alloys has been attributed to fine planar slip and superlattice dislocation structure. Dynamic embrittlement in oxidizing environments severely reduces the fatigue resistance of Ni_3Al at temperatures above 500 °C (930 °F); however, this problem has been alleviated by adding moderate amounts (for example, 8 at.%) of chromium to Ni_3Al. Fatigue/creep interactions in single crystals and directionally solidified Ni_3Al alloys have been characterized for temperatures up to 800 °C (1470 °F). Limited results indicate that the performance of single-crystal Ni_3Al alloyed with hafnium and boron is superior to that of Udimet 115 at 760 °C (1400 °F).

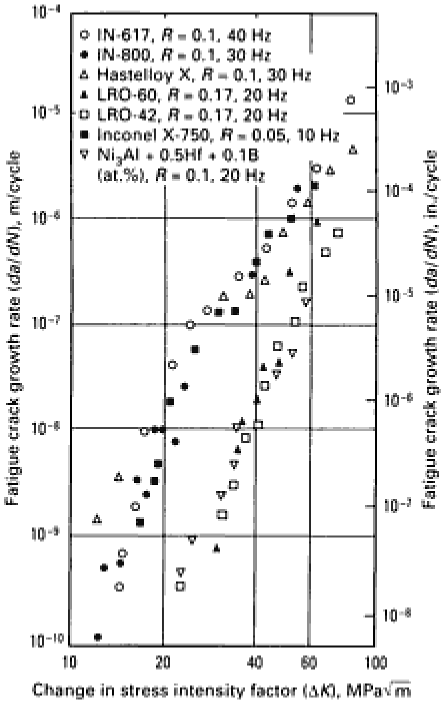

Fig. 9 Crack growth rates of nickel aluminide (Ni-23.5Al-0.5Hf-0.1B, at.%), LRO alloys [$(Fe,Ni)_3(V,Ti)$], and several high-temperature alloys tested in air at 25 °C (80 °F)

Corrosion Resistance. The oxidation and carburization resistance of Ni_3Al alloys are compared in Fig. 10 and 11. It is clear from Fig. 10 that the Ni_3Al alloys that form a protective Al_2O_3 scale on the surface have significantly better oxidation resistance that aluminum-free alloy 800. Carburization resistance is also high under both oxidizing or reducing environment (Fig. 11).

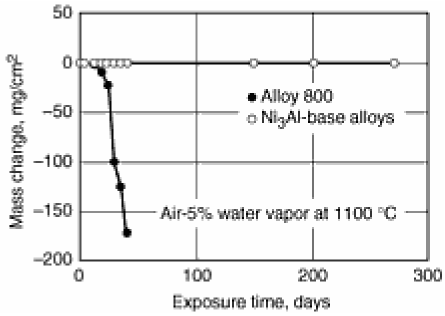

Fig. 10 Comparison of the oxidation resistance of Ni_3Al alloys with that of alloy 800 in air with 5% water vapor at 1100 °C (2010 °F)

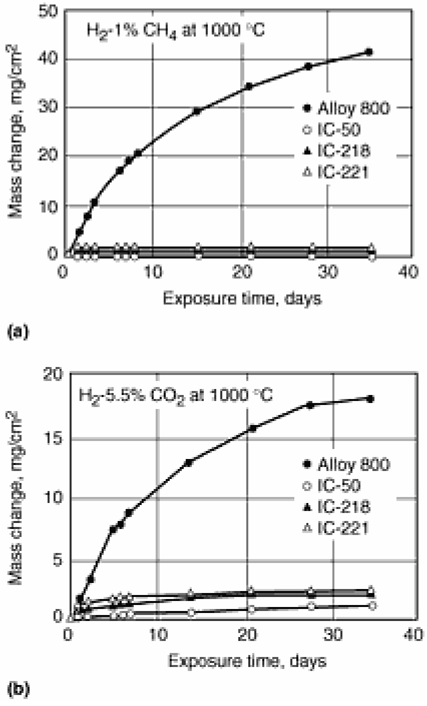

Fig. 11 Comparison of the carburization resistance of Ni_3Al alloys with that of alloy 800. (a) Oxidizing carburizing environment. (b) Reducing carburizing environment

Processing and Fabrication. Nickel aluminide parts can be produced by P/M, casting, and ingot metallurgy. Figures 7 and 8 compare the effects of processing on the properties of nickel aluminides.

The nickel aluminide powder can be produced by argon or nitrogen-gas atomization. The nickel aluminide powder can be readily consolidated to 100% density by extruding the powder in a mild steel can at 1100 °C (2010 °F) to a reduction ratio

≥9 to 1. The powder can also be consolidated by hot isostatic pressing. The extrusion-process consolidated powder has a grain structure that can be superplastic under proper conditions of temperature and strain rate.

Near-net-shape or net-shape casting of parts directly from liquid metal is a highly desirable method for the fabrication of nickel aluminides. Among the near-net-shape methods is the method of sheer fabrication by bringing liquid metal in direct contact with a rotating drum. The sheet thickness is controlled by the speed of the drum. The as-cast sheets are highly ductile, and their strength can be enhanced significantly by cold rolling.

Conventional fabrication techniques (such as hot rolling for large ingots) are ineffective because regions near the surface cool to the range of the ductility minimum, which leads to the formation of large intergranular surface cracks. Isothermal forging offers excellent possibilities for fabrication because the alloys exhibit superplastic behavior above approximately 1000 °C (1830 °F). Conventional hot forging is feasible for fine-grain alloys containing less than 0.3 at.% Zr or Hf. Cold fabrication is effective if the materials can be cast into sheet or rod forms that can be cold formed further without the need for repeated recrystallization treatments.

Alloys based on Ni_3Al are susceptible to weld cracking; however, if welding is done with care, sound welds can be made in most of the alloys. Welding speed should be reduced and the boron level has to be limited to approximately 0.1 at.% to avoid hot cracking. Oxygen is particularly detrimental: oxide scale on alloy surfaces should be removed prior to welding, and the atmosphere must be controlled to reduce oxygen during welding. Certain alloying additions (iron, for example) have been found to promote weldability. The potential applications (and the properties they would exploit) include:

- Heat-treating furnace parts (superior carburization resistance, high-temperature strength, and thermal fatigue resistance)
- Gas, water, and steam turbines (the excellent cavitation, erosion, and oxidation resistance of the alloys)
- Aircraft fasteners (low density and ease of achieving the desired strength)
- Automotive turbochargers (high fatigue resistance and low density)
- Pistons and valves (wear resistance and capability of developing a thermal barrier by high-temperature oxidation treatment)
- Bellows for expansion joints to be used in corrosive environments (good aqueous corrosion resistance)
- Tooling (high-temperature strength and wear resistance developed through preoxidation)
- Permanent molds (the ability to develop a thermal barrier coating by high-temperature oxidation)

NiAl Aluminides

Nickel-aluminum containing more than approximately 40 at.% Ni starts to form a single-phase *B*2-type ordered crystal structure based on the bcc lattice (Fig. 2). In terms of physical properties, *B*2 NiAl offers more potential for high-temperature applications than $L1_2$ Ni_3Al. It has a higher melting point (1638 °C, or 2980 °F), a substantially lower density (5.86 g/cm^3 for NiAl versus 7.50 g/cm^3 for Ni_3Al), and a higher Young's modulus (294 GPa, or 4.27×10^6 psi, versus 179 GPa, or 25.9×10^6 psi). NiAl shows a sharp increase in ductility above 400 °C (750 °F) and becomes very ductile above 600 °C (1110 °F); therefore, fabrication of NiAl at high temperatures presents no major problems.

Mechanical Properties. Widespread use of NiAl as a free-standing structural material has not yet been realized because of its poor ductility at ambient temperature and creep resistance at elevated temperatures. Limited tensile ductility has been achieved with cobalt additions. Sufficient iron additions to nickel-rich NiAl, such as Ni-30Al-20Fe (at.%) with a *B*2 structure, has resulted in approximately 2% plastic elongation. The same alloy with a fine-grain structure shows 5% elongation when produced by rapid solidification. The alloy Ni-20Al-30Fe, which has a two-phase structure (NiAl + Ni_3Al), exhibited a tensile ductility of 22% when produced by hot extrusion and a lower ductility (10 to 17%) when produced by rapid solidification.

Creep strength is improved by ternary additions of tantalum, niobium, and hafnium. Replacing some of the nickel with 15 at.% Fe also reduces the creep rate of NiAl.

The creep properties of NiAl can also be greatly improved by solid-solution hardening and particle strengthening. The best creep resistance obtained so far was produced by reinforcing NiAl with AlN dispersoids that were introduced by milling NiAl powder in liquid nitrogen.

For structural use at elevated temperatures in hostile environments, the following alloy composition (at.%) has been identified:

$$\text{Ni-(49.0} \pm \text{0.6)Al-(1.0} \pm \text{0.8)Mo-(0.7} \pm \text{0.5)Nb/Ta/Zr/Hf-(0-0.5)Fe-(0.01-0.03)B/C}$$

In this case, the alloys were prepared by melting and casting, followed by hot extrusion at 900 to 1050 °C (1650 to 1920 °F). The alloys show a yield strength as high as 700 MPa (102 ksi) at room temperature and 350 MPa (31 ksi) at 1000 °C (1830 °F). The creep rate of the alloys is lower than that of binary NiAl by five to six orders of magnitude at 816 °C in air. Among the alloying elements added to NiAl, zirconium and hafnium improve creep resistance best, but reduce the tensile ductility of the alloys.

Corrosion Resistance. NiAl offers excellent oxidation resistance at high temperatures. In the 1950s and 1960s, NiAl alloys were employed as coating materials for hot components in corrosive environments. The oxidation resistance of NiAl can be further improved by alloying with yttrium and other refractory elements such as hafnium and zirconium (Fig. 12).

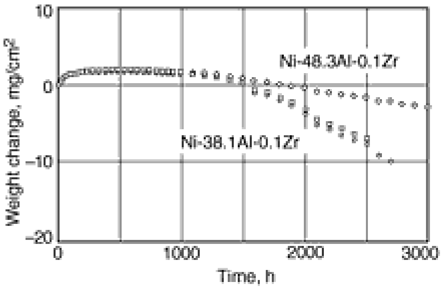

Fig. 12 Long-term (3000 h) cyclic oxidation behavior of NiAl + 0.1 at.% Zr at 1200 °C (1290 °F)

Structural Intermetallics

Iron Aluminides

Iron aluminides form bcc ordered crystal structures over the composition range of 25 to 50 at.%. The aluminide Fe_3Al exists in the ordered $D0_3$ structure up to 540 °C (1000 °F) and in the $B2$ structure between 540 and 760 °C (1000 and 1400 °F); it has a disordered structure above 760 °C (1400 °F). The $D0_3 \rightarrow B2$ transition temperature decreases, and the $B2$ ordered temperature increases with an increase in aluminum concentration above 25%. Only the $B2$ structure is stable at aluminum levels above 36%, and the single-phase field extends to approximately 50 at.% Al (FeAl). Figure 13 shows the iron-aluminum phase diagram.

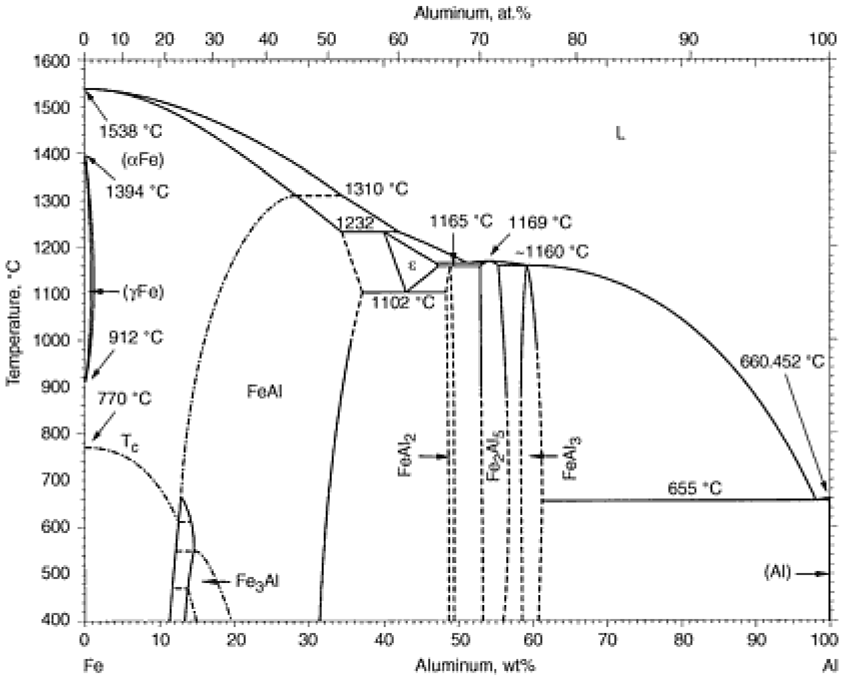

Fig. 13 The binary iron-aluminum phase diagram

The iron aluminides based on Fe_3Al and FeAl possess unique properties and have development potential as new materials for structural use. This potential is based on the capability of the aluminides to form protective Al_2O_3 scales in oxidizing and sulfidizing environments at elevated temperatures. In addition to excellent corrosion resistance, the aluminides offer low material cost, low density, and conservation of strategic elements. However, the major drawbacks of the aluminides are their low ductility and fracture toughness at ambient temperature, their poor strength at temperatures above 600 °C (1110 °F), and their susceptibility to environmental embrittlement.

Alloying Effects in Fe_3Al Aluminides. Grain structure refinement by material processing and alloy additions has been shown to be useful in increasing ductility in Fe_3Al (Fe-28 Al at.%) aluminides. Additions of titanium diboride (TiB_2) to Fe_3Al powders are very effective in reducing grain size, and they increase the tensile ductility of recrystallized materials from 2 to 5 to 7%. Stress relief following hot working of the same materials results in ductilities as high as 18%. The presence of TiB_2 particles increases the recrystallization temperature from 650 to 1100 °C (1200 to 2010 °F), which means that wrought materials will retain room-temperature ductility even after exposure to temperatures as high as 1000 °C (1830 °F). For these materials, ductility is very high at temperatures above 600 °C (1110 °F), and conventional hot fabrication techniques can be employed without difficulty.

Strength properties of these aluminides are also sensitive to microstructure and the level of aluminum. Room-temperature yield strength drops sharply with an increase of aluminum above 25%. Additions of TiB_2, which reduce the grain size of recrystallized material and stabilize the wrought structure, increase the strength significantly and cause it to he retained to higher temperatures.

A recent alloy design of Fe_3Al showed that the ductility of the aluminide prepared by melting and casting and fabricated by hot rolling can be substantially improved by increasing the aluminum content from 25 to 28 or 30 at.% and by adding chromium at a level of 2 to 6%. The increase in the aluminum concentration sharply decreases the yield strength of the aluminide. The beneficial effect of chromium may come from modifying the surface composition and reducing the water vapor and aluminum atom reaction, that is, reducing environmental embrittlement. The mechanical properties of the chromium-modified Fe_3Al alloys can be further improved by thermomechanical treatment and alloy additions of molybdenum and niobium. Some of these alloys show a tensile ductility of more than 15% at room temperature and a yield strength of close to 500 MPa (72.5 ksi) at 600 °C (1110 °F). These ductile Fe_3Al alloys are much stronger than austenitic and ferritic steels such as type 314 stainless steel and Fe-9Cr-1Mo steel. The refractory elements also substantially enhance the creep properties of the Fe_3Al alloys.

Table 4 lists several Fe_3Al alloys that were recently developed. Tensile and creep properties of wrought Fe_3Al alloys are compared with oxide dispersion strengthened (ODS) MA-956 iron-base superalloy in Fig. 14. The tensile properties of Fe_3Al alloys are similar to those of the ODS MA-956 alloy; however, its creep properties are significantly lower.

Table 4 Chemical compositions of selected Fe_3Al aluminides

Alloy[a]	Composition, wt%						
	Al	**Cr**	**B**	**Zr**	**Nb**	**C**	**Fe**
FAS	15.9	2.20	0.01	. . .	. . .	. . .	bal
FAL	15.9	5.5	0.01	0.15	. . .	. . .	bal

(a) Designations used by Oak Ridge National Laboratory, Oak Ridge, TN

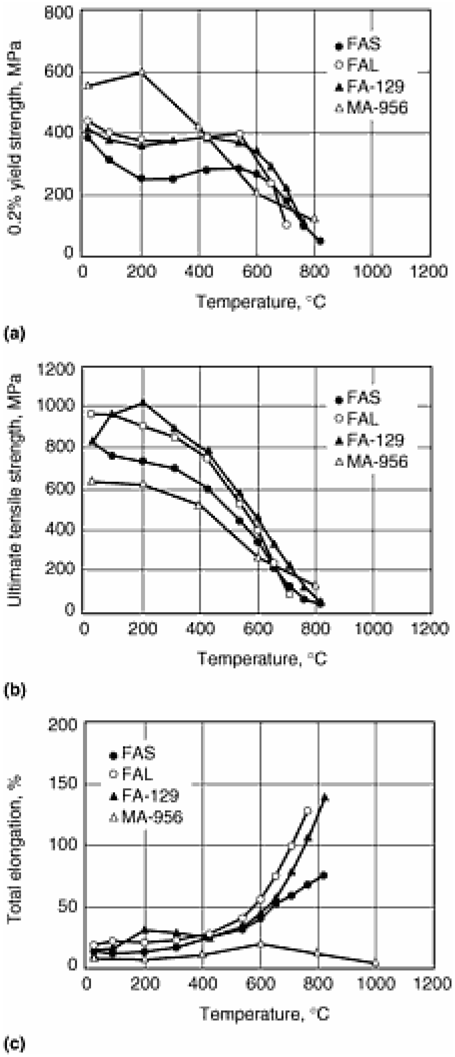

Fig. 14 Comparison of tensile properties of wrought Fe_3Al alloys with those of MA-956 alloy (Fe-20Cr-4.5Al-0.5Ti-0.5Y_2O_3). (a) 0.2% yield strength. (b) Ultimate tensile strength. (c) Total elongation. See Table 4 for Fe_3Al alloy chemical compositions

Alloying Effect in FeAl Aluminides. FeAl aluminides containing 40 at.% or more aluminum fail at room temperature by intergranular fracture with little tensile ductility. Small additions of boron (0.05 to 0.2%) suppress grain-boundary fracture and allow a small increase in ductility (~3%) of Fe-40Al, but not of Fe-50Al. The beneficial effect of boron is not nearly as dramatic in FeAl as it is in Ni_3Al, but it is nevertheless significant. The ductility of boron-doped FeAl aluminides remains low because the alloys are still embrittled by the test environment (air). It has been found that boron-doped FeAl (40% Al) exhibits a high ductility (18%) when tested in dry oxygen to avoid environmental embrittlement.

Boron additions also increase the elevated-temperature strength of FeAl, especially in combination with niobium and zirconium. For example, the creep rate can be lowered by an order of magnitude at 825 °C (1520 °F) by the combination of 0.1% Zr and 0.2% B.

More recent alloy development studies have focused on a base alloy of Fe-36Al (at.%) alloyed with the elements listed in Table 5. The most effective elements for increasing high-temperature strength and room-temperature ductility of these FeAl alloys were small additions of molybdenum, zirconium, and boron in combination, with the synergistic effects being much more potent than the single element effects. While zirconium and boron additions were very important for improved room-temperature ductility, Mo + Zr + B additions produced the best tensile and creep-rupture strength at 600 °C (1110 °F) in an alloy designated FA-362 (Table 5). The FA-362 alloy also showed the highest room-temperature ductility in air (11.8%). Preoxidation at 700 °C (1290 °F) further increased the tensile ductility to 14.7%. Figure 15 compares the elevated-temperature yield strengths of various FeAl alloys listed in Table 5 with those of two high-speed tool steels.

Table 5 Chemical compositions of developmental FeAl (Fe-35.8 at.% Al) alloys

Alloy[a]	Composition, at.%						
	Cr	**Nb**	**Ti**	**Mo**	**Zr**	**C**	**B**
FA-350	. . .	. . .	. . .	. . .	0.05	. . .	0.24
FA-362	. . .	. . .	. . .	0.2	0.05	. . .	0.24
FA-372	. . .	. . .	. . .	0.2	0.05	. . .	. . .
FA-383	. . .	. . .	. . .	. . .	0.05	. . .	. . .
FA-384	2	. . .	. . .	0.2	0.05	. . .	. . .
FA-385	. . .	. . .	. . .	0.2	0.05	0.13	. . .
FA-386	. . .	. . .	. . .	0.2	0.05	0.24	. . .
FA-387	. . .	. . .	. . .	0.2	. . .	. . .	0.24
FA-388	. . .	. . .	. . .	0.2	. . .	0.25	. . .
FA-385M1	. . .	. . .	. . .	0.2	0.05	0.13	0.01
FA-385M2	. . .	. . .	. . .	0.2	0.05	0.13	0.021
FA-385M3	2	. . .	. . .	0.2	0.05	0.13	. . .
FA-385M4	. . .	0.5	. . .	0.2	0.05	0.13	. . .
FA-385M5	2	0.5	. . .	0.2	0.05	0.13	. . .
FA-385M6	2	0.5	. . .	0.2	0.05	0.25	. . .
FA-385M7	2	0.5	. . .	0.2	0.1	0.25	. . .
FA-385M8	2	0.5	0.05	0.2	0.05	0.13	. . .
FA-385M9	2	0.5	0.05	0.2	0.05	0.25	. . .
FA-385M10[b]	2	0.5	0.05	0.2	0.05	0.13	. . .

(a)	Designations used by Oak Ridge National Laboratory, Oak Ridge, TN.
(b)	Also contains 0.5% Ni, 0.3% Si, and 0.016% P (at.%).
(c)	Also contains 0.25% W (at.%)

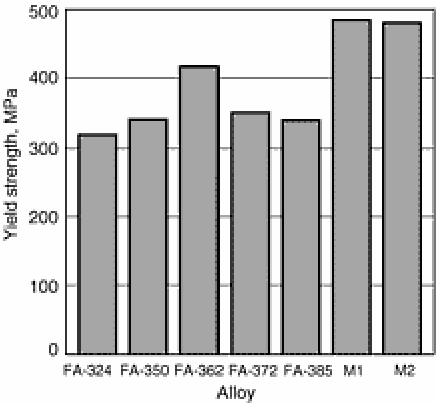

Fig. 15 Yield strength of several FeAl alloys tensile tested at 600 °C (1110 °F) in air. Specimens were punched from thin sheets, hot rolled at 850 to 900 °C (1560 to 1650 °F), and heat treated for 1 h at 700 to 800 °C (1290 to 1470 °F) prior to testing. See Table 5 for alloy compositions.

Environmental Embrittlement. For more than 45 years, the iron aluminides have been known to be brittle it ambient temperatures; however, the major cause of the brittleness has only recently been identified. The data in Table 6 indicate the effect of test environment on the room-temperature tensile properties of FeAl (36.5% Al) and Fe_3Al (28% Al). Yield strength is not sensitive to environment, but ultimate tensile strength is generally correlated with tensile ductility, which depends strongly on test environment. Aluminides tested in air had a ductility of 2 to 4%. FeAl tested in dry oxygen had a ductility of 17.6%, and Fe_3Al tested in vacuum and dry oxygen had a ductility of 12 to 13%. The water vapor test confirmed the low ductility found in the air tests, indicating that moisture in air is the embrittling agent.

Table 6 Effect of selected test environments on room-temperature tensile properties of iron aluminides

Test environment (gas pressure)	Elongation, %	Yield strength		Ultimate tensile strength	
		MPa	**ksi**	**MPa**	**ksi**
Fe_3Al (28% Al)[(a)]					
Air	4.1	387	56	559	81
Vacuum (~1 × 10^{-4} Pa)	12.8	387	56	851	123
Argon + 4% H_2 (6.7 × 10^4 Pa)	8.4	385	55.8	731	106
Oxygen (6.7 × 10^4 Pa)	12.0	392	56.8	867	126
Water vapor (1.3 × 10^3 Pa)	2.1	387	56	475	69
FeAl (36.5% Al)[(a)]					
Air	2.2	360	52.2	412	60
Vacuum (<1 × 10^{-4} Pa)	5.4	352	51	501	73
Argon + 4% H_2 (6.7 × 10^4 Pa)	6.2	379	55	579	84
Oxygen (6.7 × 10^4 Pa)	17.6	360	52.2	805	117

(a) All specimens were annealed 1 h at 900 °C (1650 °F) + 2 h at 700 °C (1290 °F).

Embrittlement is expected to involve the following chemical reaction at metal surfaces:

$$2Al + 3H_2O \rightarrow Al_2O_3 + 6H^+ + 6e^-$$

The reaction of water vapor with aluminum atoms at crack tips results in the formation of atomic hydrogen that drives into the metal and causes crack propagation. The fact that yield strength (Table 6) is insensitive to ductility and test environment is consistent with the mechanisms of hydrogen embrittlement observed in other ordered intermetallic alloys.

Corrosion Resistance. As stated earlier, the iron aluminides are highly resistant to oxidation and sulfidation at elevated temperatures. The oxidation resistance generally increases with increasing aluminum content; the major products are α-Al_2O_3 and trace amounts of iron oxides when the aluminides are oxidized at temperatures above 900 °C (1650 °F). Cyclic oxidation of Fe-40Al alloyed with up to 1 at.% Hf, Zr, and B produced little degradation at temperatures up to 1000 °C (1830 °F). Aluminide specimens tested at 700 and 870 °C (1290 and 1600 °F) showed no indication of attack in sulfidizing environments, except for the formation of a thin layer of oxides with a thickness in an interference color range. As shown in Fig. 16, the iron aluminum alloys exhibited corrosion rates lower than those of conventional Fe-Cr-Ni alloys (including coating material) by a couple of orders of magnitude when tested in a severe sulfidizing environment at 800 °C (1470 °F). In addition, the aluminides with more than 30% Al are very resistant to corrosion in molten nitrate salt environments at 650 °C (1200 °F). Because of their excellent corrosion resistance, iron aluminides are being considered for use in molten salt systems for chemical air separation, automotive exhaust systems, immersion heaters, heat exchangers, catalytic conversion vessels, chemical production systems, and coal conversion systems.

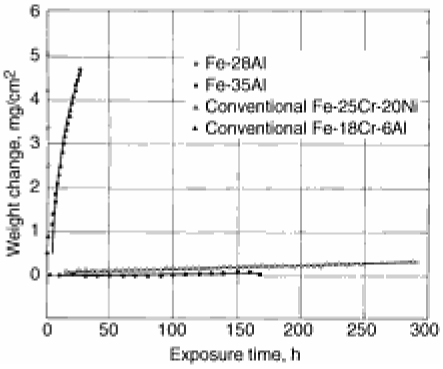

Fig. 16 Comparison of the corrosion behavior of iron aluminides with that of conventional iron-base alloys Fe-18Cr-6Al (the coating material) and Fe-25Cr-20Ni. All materials were exposed to a severe sulfidizing environment at 800 °C (1470 °F).

Titanium Aluminides

Because of their low density, titanium aluminides based on Ti_3Al and TiAl are attractive candidates for applications in advanced aerospace engine components (latter stages of the compressor or turbine sections), airframe components, and automotive valves and turbochargers. Table 1 presents the characteristics of titanium aluminides alongside those of other aluminides; the creep behavior of titanium aluminides is compared with that of conventional titanium alloys in Fig. 17. Despite a lack of fracture resistance (low ductility, fracture toughness, and fatigue crack growth rate), the titanium aluminides Ti_3Al (α-2) and TiAl (γ) have great potential for enhanced performance. Table 7 compares properties of these aluminides with those of conventional titanium alloys and superalloys. Because they have slower diffusion rates than conventional titanium alloys, the titanium aluminides feature enhanced high-temperature properties such as strength retention, creep and stress rupture and fatigue resistance.

Table 7 Properties of titanium aluminides, titanium-base conventional alloys, and nickel-base superalloys

Property	Conventional titanium alloys	Ti_3Al	TiAl	Nickel-base superalloys
Density, g/cm^3	4.5	4.1-4.7	3.7-3.9	8.3
Modulus, GPa (10^6 psi)	96-100 (14-14.5)	100-145 (14.5-21)	160-176 (23.2-25.5)	206 (30)
Yield strength[(a)], MPa (ksi)	380-1150 (55-167)	700-990 (101-144)	400-650 (58-94)	. . .
Tensile strength[(a)], MPa (ksi)	480-1200 (70-174)	800-1140 (116-165)	450-800 (65-116)	. . .
Creep limit, °C (°F)	600 (1110)	760 (1400)	1000 (1830)	1090 (1995)
Oxidation limit, °C (°F)	600 (1110)	650 (1200)	900 (1650)	1090 (1995)
Ductility at room temperature, %	20	2-10	1-4	3-5
Ductility at high temperature, %	High	10-20	10-60	10-20
Structure	hcp/bcc	$D0_{19}$	$L1_0$	fcc/L_2

(a) At room temperature

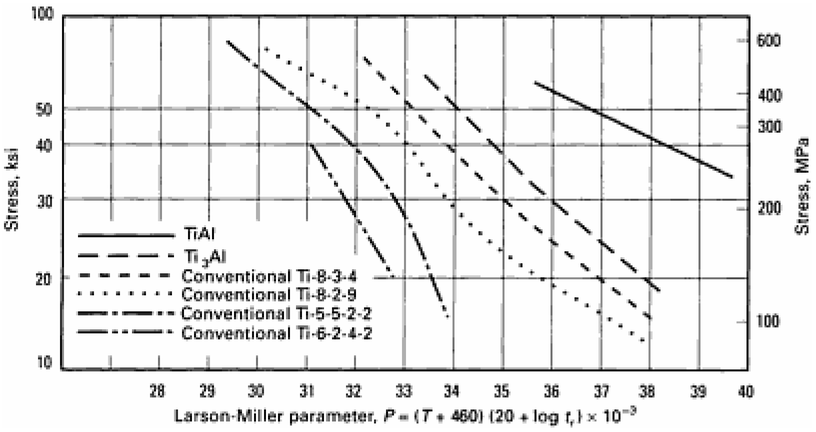

Fig. 17 Comparison of the creep behavior of conventional titanium alloys and titanium aluminide intermetallics

Another negative feature of titanium aluminides, in addition to their low ductility at ambient temperatures, is their oxidation resistance, which is lower than desirable at elevated temperatures. The titanium aluminides are characterized by a strong tendency to form TiO_2, rather than the protective Al_2O_3, at high temperatures. Because of this tendency, a key factor in increasing the maximum-use temperatures of these aluminides is enhancing their oxidation resistance while maintaining adequate levels of creep and strength retention at elevated temperatures.

Alpha-2 Alloys

The α-2 (Ti_3Al) intermetallic has an ordered $D0_{19}$ structure (see Fig. 2). As shown on the titanium-aluminum phase diagram (Fig. 18), Ti_3Al has a wide range of composition stability, with aluminum contents of 22 to 39 at.%. The compound is congruently disordered at a temperature of 1180 °C (2155 °F) and an aluminum content of 32 at.%. The stoichiometric composition, Ti-25Al, is stable up to approximately 1090 °C (1995 °F).

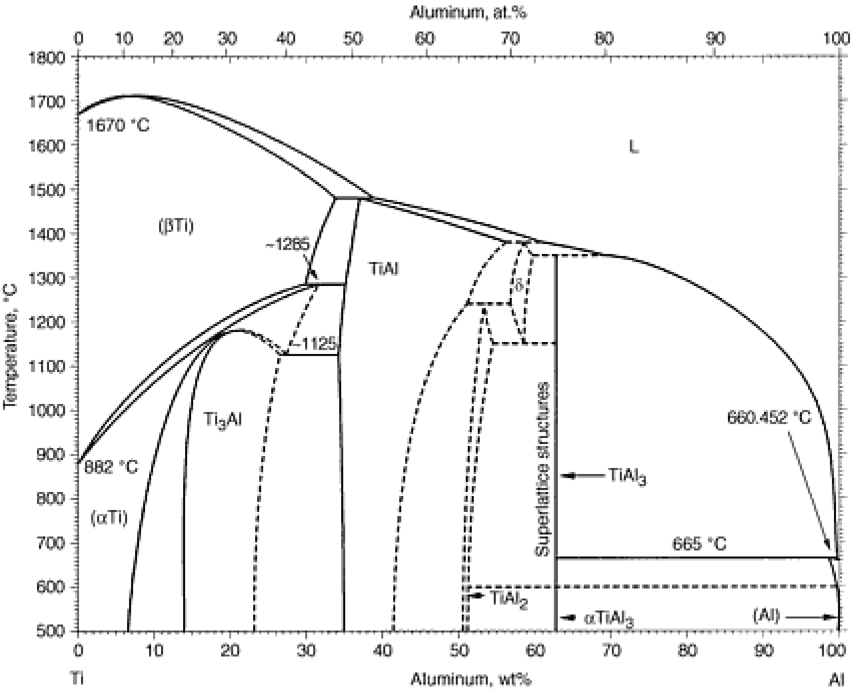

Fig. 18 The titanium-aluminum binary phase diagram

The semicommercial and experimental α-2 alloys developed are two phase (α-2 + β/*B*2), with contents of 23 to 25 at.% Al and 11 to 18 at.% Nb. Alloy compositions with current engineering significance are Ti-24Al-11Nb, Ti-25Al-10Nb-3V-1Mo, Ti-25Al-17Nb-1Mo, and modified alloy compositions such as Ti-24.5Al-6Nb-6(Ta,Mo,Cr,V). Increasing the niobium content generally enhances most material properties, although excessive niobium can degrade creep performance. Niobium can be replaced by specific elements for improved strength (molybdenum, tantalum, or chromium), creep resistance (molybdenum), and oxidation resistance (tantalum, molybdenum). However, for full optimization of mechanical properties, control of the microstructure must be maintained, particularly for tensile, fatigue, and creep performance. Microstructural features, such as primary α-2 grain size and volume fraction and secondary α-2 plate morphology and thickness, are varied by thermomechanical processing.

Typical mechanical properties for a number of α-2 alloys are listed in Table 8. Production of two-phase alloys by alloying Ti_3Al with β-stabilizing elements results in up to a doubling of strength. Interface strengthening of the two-phase mixture appears to be predominantly responsible for the increased strength, but other strengthening factors, such as long-range order, solid solution, and texture effects, also contribute.

Table 8 Properties of α-2 Ti_3Al alloys with various microstructures

Alloy	Microstructure(a)	Yield strength		Ultimate tensile strength		Elongation, %	Plane-strain fracture toughness (K_{Ic})		Creep rupture(b)
		MPa	**ksi**	**MPa**	**ksi**		**MPa** $\sqrt{m}$	**ksi** $\sqrt{in.}$	
Ti-25Al	E	538	78	538	78	0.3	. . .	. . .	. . .
Ti-24Al-11Nb	W	787	114	824	119	0.7	. . .	. . .	44.7
	FW	761	110	967	140	4.8	. . .	. . .	. . .
Ti-24Al-14Nb	W	831	120	977	142	2.1	. . .	. . .	59.5
Ti-25Al-10Nb-3V-1Mo	W	825	119	1042	151	2.2	13.5	12.3	>360
	FW	823	119	950	138	0.8	. . .	. . .	. . .
	C + P	745	108	907	132	1.1	. . .	. . .	. . .
	W + P	759	110	963	140	2.6	. . .	. . .	. . .
	FW + P	942	137	1097	159	2.7	. . .	. . .	. . .
Ti-24.5Al-17Nb	W	952	138	1010	146	5.8	28.3	25.7	62
	W + P	705	102	940	136	10.0	. . .	. . .	. . .

(a) E, equiaxed α-2; W, Widmanstätten; FW, fine Widmanstätten; C, colony structure; P, primary α-2 grains.

(b) Time to rupture, h, at 650 °C (1200 °F) and 380 MPa (55 ksi)

A fine Widmanstätten microstructure with a small amount of primary α-2 grains exhibits better ductility than microstructures with a coarse Widmanstätten microstructure or an aligned acicular α-2 morphology. A detailed investigation into the effect of microstructure on creep behavior in Ti-25Al-10Nb-3V-1Mo has shown that the colony-type microstructure shows better creep resistance than other microstructures. Creep resistance of Ti-25-10-3-1 is raised by a factor of ten in the steady-state regime over that of conventional alloy Ti-1100 (Ti-6Al-3Sn-4Zr-0.4Mo-0.45Si) and two orders of magnitude over that of Ti-6Al-2Sn-4Zr-2Mo-0.1Si. However, 0.4% creep strain in Ti-25-10-3-1 is reached within 2 h.

Additions of silicon and zirconium appear to improve creep resistance, but the most significant improvement is attained by increasing the aluminum content to 25 at.% and limiting β-stabilizing elements to approximately 12 at.%. However, the Ti-24.5Al-17Nb-1Mo alloy exhibits a rupture life superior to that of other α-2 alloys.

Orthorhombic Alloys

At higher niobium levels, the α-2 phase evolves to a new ordered orthorhombic structure that is based on the composition Ti_2AlNb (O phase). This has been observed in titanium aluminides with compositions near Ti-(21-25)Al-(21-27)Nb (at.%).

Although the orthorhombic alloys have a lower use temperature than the γ aluminides described in the section "Gamma Alloys" (approximately 650 °C, or 1200 °F), they offer much higher absolute strengths. Room-temperature tensile strengths on the order of 1380 MPa (200 ksi) with close to 5% elongation have been reported. In addition, 0.2% yield strengths in the range of 590 to 690 MPa (86 to 100 ksi) at 700 °C (1290 °F) have also been reported for Ti-21Al-25Nb (at.%) alloy. This material had a room-temperature yield strength of approximately 1070 MPa (155 ksi) with 3.5% elongation.

The ordered orthorhombic alloys having the best combination of tensile, creep, and fracture toughness properties are two-phase O + β alloys such as Ti-22Al-27Nb (at.%). Table 9 lists the elevated-temperature tensile properties of such alloys.

Table 9 Tensile properties of a two-phase (O + β) alloy (Ti-22Al-27Nb at.%)

Test temperature		Aging treatment	Tensile yield strength		Ultimate tensile strength		Elongation, %
°C	**°F**		**MPa**	**ksi**	**MPa**	**ksi**	
22	72	None	1056	153	1152	167	3.4
		None	1028	149	1083	157	2.2
		540 °C (1000 °F), 100 h	1083	157	1166	169	3.3
		540 °C (1000 °F), 100 h	1090	158	1159	168	2.8
		650 °C (1200 °F), 100 h	1090	158	1145	166	2.6
		650 °C (1200 °F), 100 h	1076	156	1145	166	2.5
		760 °C (1400 °F), 100 h	987	143	1076	156	5.2
		760 °C (1400 °F), 100 h	966	140	1083	157	5.0
540	1000	None	849	123	1007	146	14.3
		None	856	124	1049	152	14.3
		540 °C (1000 °F), 100 h	876	127	1049	152	17.9
		540 °C (1000 °F), 100 h	890	129	1070	155	16.1
650	1200	None	794	115	938	136	14.3
		None	807	117	945	137	12.5
		650 °C (1200 °F), 100 h	794	115	938	136	10.7
		650 °C (1200 °F), 100 h	807	117	952	138	10.7
760	1400	None	559	81	787	114	10.7
		None	593	86	766	114	14.3
		760 °C (1400 °F), 100 h	462	67	649	94	21.4

Gamma Alloys

The γ-TiAl phase has an $L1_0$ ordered face-centered tetragonal structure (Fig. 2), which has a wide range (49 to 66 at.% Al) of temperature-dependent stability (Fig. 18). The γ-TiAl phase apparently remains ordered up to its melting point of approximately 1450 ° (2640 °F).

They γ alloys of engineering importance contain approximately 45 to 48 at.% Al and 1 to 10 at.% M, with M being at least one of the following: vanadium, chromium, manganese, niobium, tantalum, and tungsten. These alloys can be divided into two categories: single-phase (γ) alloys and two-phase (γ + α-2) materials. The (α-2 + γ)/γ phase boundary at 1000 °C (1830 °F) occurs at an aluminum content of approximately 49 at.%, depending on the type and level of solute M. Single-phase γ alloys contain third alloying elements such as niobium or tantalum that promote strengthening and further enhance oxidation resistance. Third alloying elements in two-phase alloys can raise ductility (vanadium, chromium, and manganese), increase oxidation resistance (niobium and tantalum) or enhance combined properties.

Material Processing. Gamma alloys are processed by conventional methods, including casting, ingot metallurgy, and P/M. Important alloying/melting processes include induction skull melting, vacuum arc melting, and plasma melting. Other methods under study include mechanical alloying, spray forming, shock reactive synthesis, physical vapor deposition, and hot pressing and rolling of elemental sheet into multilayer composite sheets. By appropriate thermomechanical processing (TMP), the morphology of the phases in nominally γ alloys can be adjusted to produce either lamellar or equiaxed morphologies, or a mixture of the two.

Mechanical Properties. Table 10 lists tensile properties and fracture toughness of γ alloys as functions of processing/microstructure and temperature. Ternary alloys of Ti-48Al with approximately 1 to 3% V, Mn, or Cr exhibit enhanced ductility, but Ti-48Al alloys with approximately 1 to 3% Nb, Zr, Hf, Ta, or W show lower ductility than binary

Ti-48Al. The brittle-ductile transition (BDT) occurs at 700 °C (1290 °F) in Ti-56Al and at lower temperatures with decreasing aluminum levels. Increased room-temperature ductility generally results in a reduced BDT temperature. Above the BDT temperature, ductility increases rapidly with temperature, approaching 100% at 1000 °C (1830 °F) for the most ductile γ alloy compositions. The trend bands for variations in yield strength and tensile ductility with test temperature are shown in Fig. 19. The elastic moduli of γ alloys range from 160 to 176 GPa (23×10^6 to 25.5×10^6 psi) and decrease slowly with temperature.

Table 10 Tensile properties and fracture toughness values of gamma titanium aluminides tested in air

Alloy designation and composition, at.%	Processing and microstructure	Temperature		Yield strength		Tensile strength		Elongation, %	Fracture toughness[(a)], K_q	
		°C	**°F**	**MPa**	**ksi**	**MPa**	**ksi**		**MPa$\sqrt{m}$**	**ksi$\sqrt{in.}$**
48-1-(0.3C)/Ti-48Al-1V-0.3C-0.2O	Forging + HT/duplex	RT	RT	392	57	406	59	1.4	12.3	11.2
		437	819	. . .	. . .	. . .	. . .	. . .	22.8	20.7
		760	1400	320	46	470	68	10.8	. . .	. . .
	Casting/duplex	RT	RT	490	71	. . .	. . .	. . .	24.3	22.1
48-1(0.2C)/Ti-48Al-1V-0.2C-0.14O	Forging + HT/duplex + NL	RT	RT	480	70	530	77	1.5	. . .	. . .
		815	1500	360	52	450	65	. . .	. . .	. . .
48-2-2/Ti-48Al-2Cr-2Nb	Casting + HIP + HT/duplex	RT	RT	331	48	413	60	2.3	20-30	18-27
		760	1400	310	45	430	62	. . .	. . .	. . .
	Extrusion + HT/duplex	RT	RT	480	70	. . .	. . .	3.1	. . .	. . .
		760	1400	403	58	. . .	. . .	40	. . .	. . .
		870	1600	330	48	. . .	. . .	53	. . .	. . .
	Extrusion + HT/FL	RT	RT	454	66	. . .	. . .	0.5	. . .	. . .
		760	1400	405	59	. . .	. . .	3.0	. . .	. . .
		870	1600	350	51	. . .	. . .	19	. . .	. . .
	P/M extrusion + HT/NL	RT	RT	510	74	597	87	2.9	. . .	. . .
		700	1290	421	61	581	84	5.2	. . .	. . .
G1/Ti-47Al-1Cr-1V-2.6Nb	Forging + HT/duplex	RT	RT	480	70	548	79	2.3	12	10.8
		600	1110	383	56	507	74	3.1	16	14.6
		800	1470	324	47	492	71	55	. . .	. . .
	Forging + HT/FL	RT	RT	330	48	383	56	0.8	30-36	27-33
		800	1470	290	42	378	55	1.5	40-70	36-64
Sumitomo/Ti-45Al-1.6Mn	Reactive sintering/NL	RT	RT	465	67	566	82	1.4	. . .	. . .
		800	1470	370	54	540	78	14	. . .	. . .
ABB alloy/Ti-47Al-2W-0.5Si	Casting + HT/duplex	RT	RT	425	62	520	75	1.0	22	20
		760	1400	350	51	460	67	2.5	. . .	. . .
47XD/Ti-47Al-2Mn-2Nb-0.8TiB$_2$	Casting + HIP + HT/NL + TiB$_2$	RT	RT	402	58	482	70	1.5	15-16	13.6-14.6
		760	1400	344	50	458	66	. . .	. . .	. . .
45XD/Ti-45Al-2Mn-2Nb-0.8TiB$_2$	Casting + HIP + HT	RT	RT	570	83	695	101	1.5	15-19	13.6-17.3
		600	1110	440	64	650	94	. . .	. . .	. . .
		760	1400	415	60	510	74	19	. . .	. . .
GE alloy 204b/Ti-46.2Al-*x* Cr-*y* (Ta,Nb)	Casting + HIP + HT/NL	RT	RT	442	64	575	83	1.5	34.5	31.4
		760	1400	382	55.4	560	81	12.4	. . .	. . .
		840	1545	381	55.2	549	80	12.2	. . .	. . .
Ti-47Al-2Nb-2Cr-1Ta	Casting + HIP + HT/duplex	RT	RT	430	62	515	75	1.0	. . .	. . .
		800	1470	363	53	495	72	23.3	. . .	. . .
		870	1600	334	48	403	58	14.6	. . .	. . .
Ti-47Al-2Nb-1.75Cr	PM casting + HIP + HT	RT	RT	429	62	516	75	1.4	. . .	. . .
		760	1400	286	41	428	62	13.3	. . .	. . .
		815	1500	368	53	531	77	23.3	. . .	. . .
Alloy 7/Ti-46Al-4Nb-1W	Extrusion + HT/NL	RT	RT	648	94	717	104	1.6	. . .	. . .
		760	1400	517	75	692	100	. . .	. . .	. . .
Alloy K5/Ti-46.5Al-2Cr-3Nb-0.2W	Forging + HT/duplex	RT	RT	462	67	579	84	2.8	11	10
		800	1470	345	50	468	68	40	. . .	. . .
	Forging + HT/RFL	RT	RT	473	69	557	81	1.2	20-22	18-20
		800	1470	375	54	502	73	3.2	. . .	. . .
		870	1600	362	53	485	70	12.0	. . .	. . .

HT, heat treated; HIP, hot-isostatically pressed; P/M, powder metallurgy; PM, permanent mold (casting); NL, nearly lamellar; FL, fully lamellar; RFL, refined fully lamellar; RT, room temperature.

(a) K_q = the provisional K_{Ic} value

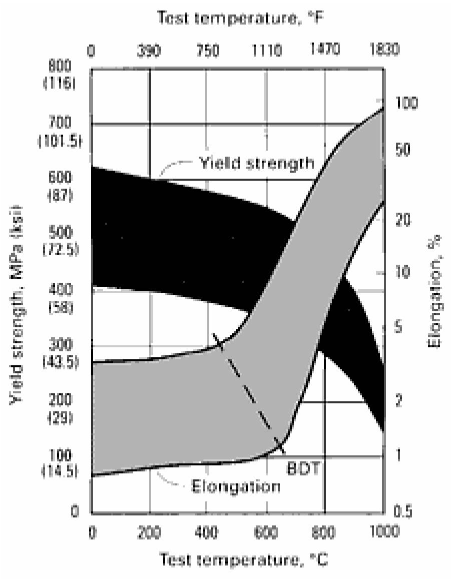

Fig. 19 Ranges of yield strength and tensile elongation as functions of test temperature for γ-TiAl alloys. BDT, brittle-ductile transition

Low-cycle fatigue experiments suggest that fine grain sizes increase fatigue life at temperatures below 800 °C (1470 °F). Fatigue crack growth rates for γ alloys are more rapid than those for superalloys, even when density is normalized. Both fracture toughness and impact resistance are low at ambient temperatures, but fracture toughness increases with temperature; for example, the plane-strain fracture toughness (K_{Ic}) for Ti-48Al-1V-0.1C is 24 MPa$\sqrt{m}$ (21.8 ksi$\sqrt{in.}$) at room temperature. Fracture toughness is strongly dependent on the volume fraction of the lamellar phase. In a two-phase quaternary γ alloy, a fracture toughness of 12 MPa$\sqrt{m}$ (10.9 ksi$\sqrt{in.}$) is observed for a fine structure that is almost entirely γ; K_{Ic} is greater than 20 MPa$\sqrt{m}$ (18.2 ksi$\sqrt{in.}$) when a large volume fraction of lamellar grains are present. Creep properties of γ alloys, when normalized by density, are better than those of superalloys, but they are strongly influenced by alloy chemistry and TMP. Increased aluminum content and additions of tungsten or carbon increase creep resistance. Increasing the volume fraction of the lamellar structure enhances creep properties but lowers ductility. The level of creep strain from elongation upon initial loading and primary creep is of concern because it can exceed projected design levels for maximum creep strain in the part.

Composites. Gamma titanium aluminides also serve as the matrix for titanium-matrix composites. Investment cast Ti-47Al-2Nb-2Mn (at.%) + 0.8 vol% TiB_2 and Ti-45Al-2Nb-2Mn (at.%) + 0.8 vol% TiB_2 XD (exothermic dispersion) alloys have been developed. These alloy form in situ titanium diborides that cause grain refinement and subsequent enhancement of mechanical and physical properties. The XD-type of in situ reinforcements offer better thermal stability than conventional metal-matrix composites and the opportunity to introduce reinforcements in the micron scale range (at 0.8 vol%, the TiB_2 is simply serving as a grain refiner). The XD aluminides offer excellent fatigue properties, with endurance limits in the range of 95 to 115% of the yield strength (non-XD γ alloys exhibit similar behavior). The high fatigue strength is attributed to the microstructural refinement mentioned previously and a strain aging effect that occurs during loading. One major gas turbine engine manufacturer is studying XD γ-aluminide blades for the last stage low-pressure turbine in an aircraft engine that currently uses IN-713 blades. Service temperature is in the range of 650 to 700 °C (1200 to 1290 °F). XD titanium aluminide composites are also being used for applications such as missile fins. Ti-47Al-2V + 7 vol% TiB_2 has a higher strength than 17-4PH steel above 600 °C (1110 °F) and a higher modulus at approximately 750 °C (1380 °F). These improvements extend the operating temperature of the missile wing, which led to a redesign utilizing the XD composite. Table 10 lists tensile properties of XD composites.

Oxidation Resistance. Although the γ class of titanium aluminides offers oxidation and interstitial (oxygen, nitrogen) embrittlement resistance superior to that of the α-2 and orthorhombic (Ti_2AlNb) classes of titanium aluminides, environmental durability is still a concern. especially at temperatures approximately 750 to 800 °C (1380 to 1470 °F) in air. This is because, as stated earlier in this article, all titanium aluminides are characterized by a strong tendency to form TiO_2, rather than the protective Al_2O_3 scale, at elevated temperature. To improve the oxidation resistance of γ aluminides, two areas are being explored: alloy development and the development of improved protective coatings.

Ternary and higher-order alloying additions can reduce the rate of oxidation of γ alloys. Of particular benefit are small (1 to 4%) ternary additions of tungsten, niobium, and tantalum. When combined with quaternary additions of 1 to 2% Cr or Mn, further improvement in oxidation resistance is gained. However, it is important to stress that these small alloying additions do not result in continuous Al_2O_3 scale formation. Rather, a complex intermixed Al_2O_3/TiO_2 scale is still formed, but the rate of growth of this scale is reduced.

Further improvements in oxidation resistance can be obtained via protective coatings. Three general coating alloy approaches have been taken for protecting titanium aluminides: MCrAlY (M = Ni, Fe, Co), aluminizing, and silicides/ceramics. Protection of titanium aluminides under oxidizing conditions has been achieved with all three approaches; however, the fatigue life of coated material is often reduced to below that of uncoated material.

The degradation in the fatigue life of titanium aluminides by coatings results from three main factors: the formation of brittle coating/substrate reaction zones (chemical incompatibility), the brittleness of the coating alloy, and the differences in the coefficient of thermal expansion (CTE) between the coating and the substrate. MCrAlY coatings, which are successfully used to protect nickel-, iron-, and cobalt-base superalloys, are not chemically compatible with titanium aluminides and form brittle coating/substrate reaction zones at 800 °C. Aluminizing treatments result in the surface formation of the $TiAl_3$ and $TiAl_2$ phases, which are brittle and exhibit CTE mismatches with α-2 orthorhombic, and γ titanium aluminides. Silicide and ceramic coatings are also generally too brittle to survive fatigue conditions.

The ideal oxidation-resistant coating for γ alloys would be Ti-Al based for optimal chemical and mechanical compatibility with γ substrates, be capable of forming a continuous Al_2O_3 scale for protection from both oxidation and interstitial oxygen/nitrogen embrittlement, and possess reasonable mechanical properties to survive high-cycle fatigue. No ideal combination of these properties exists at present. However, reasonable compromises have been achieved with coating alloys based in the Ti-Al-Cr system. These coatings have been applied by sputtering (Ti-44Al-28Cr on Ti-47Al-2Cr-2Ta), hot isostatic pressing (Ti-44Al-28Cr and Ti-50Al-20Cr coatings), and low-pressure plasma spraying. Figure 20 shows the results of interrupted weight gain oxidation data for Ti-48Al-2Cr-2Nb coated with Ti-51Al-12Cr. These tests showed that the coating successfully protected the substrate at 800 °C (1470 °F) and 1000 °C (1830 °F) in air.

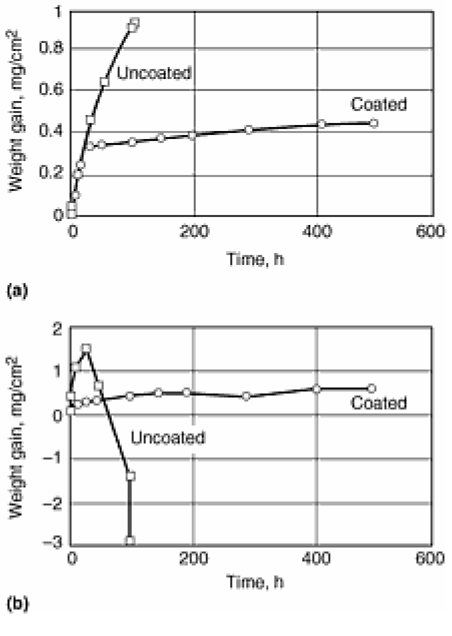

Fig. 20 The effect of a low-pressure plasma sprayed Ti-51Al-12Cr coating on the (a) 800 °C (1470 °F) and (b) 1000 °C (1830 °F) interrupted oxidation behavior of a Ti-48Al-2Cr-2Nb γ-TiAl alloy in air

Other Intermetallics of Importance

Ni_3Si Alloys. The silicide Ni_3Si is the major constituent of the commercial cast alloy Hastelloy D, a corrosion-resistant alloy with the unique ability to resist attack by sulfuric acid solutions (see the Section "Nickel and Nickel Alloys" in this Handbook). Some alloys based on Ni_3Si, such as Ni-18.9Si-3.2Cr-0.6Hf-0.15B (at.%), are as strong as nickel-base superalloy IN 718 at room and intermediate temperatures and have the potential to be used as structural materials for chemical and petrochemical applications.

Fe_3Si Alloys. A commercial alloy named Sendust based on Fe_3Si and Fe_3Al has been developed for soft magnetic applications; its typical composition is Fe-9.6Si-5.4Al (wt%). Sendust has been used as a magnetic head core material because of its superior magnetic properties and its resistance to wear and corrosion. Magnetic properties of Sendust are given in the article "Magnetically Soft Materials" in this Section (see Fig. 9 in that article).

$MoSi_2$ is attractive because of its high electrical and thermal conductivities and excellent oxidation resistance at high temperatures. $MoSi_2$ has been used commercially for electrical heating elements in high-temperature furnaces under the trade name of Kanthal, which contains roughly 80% $MoSi_2$ and 20% glass ceramic compounds. Properties of $MoSi_2$ are given in the article "Electrical Resistance Alloys" in this Section.

NiTi. Nitinol, based on the equiatomic NiTi intermetallic, is the major material used for shape memory alloys for industrial, consumer, and medical applications. Detailed information on such alloys can be found in the article "Shape Memory Alloys" in this Section.

$SmCo_5$ alloys, produced by P/M processes, are widely used for magnetic applications. Properties and applications for such cobalt-rare earth alloys are given in the article "Permanent Magnet Materials" in this Section.

Nb_3Sn is an important constituent in superconducting devices. Properties and applications of this compound are described in the article "Superconducting Materials" in this Section.

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Beryllium

Introduction

BERYLLIUM, because of its unusual combination of physical and mechanical properties, finds its way into specialized applications when its relatively high cost can be justified. It has a very low density (1.848 g/cm^3, or 0.067 lb/in.^{3}), a moderately high melting point (1283 °C, or 2341 °F), and a high elastic modulus (303 GPa, or 44 × 10^6 psi). It has good electrical conductivity (40% IACS) and thermal conductivity (210 W/m · K, or 121 Btu/ft · h · F).

Unalloyed beryllium is used in weapons, spacecraft, rocket nozzles, structural tubing, optical components, and precision instruments. The specific modulus, that is, the ratio of elastic modulus to density, is higher than that of aluminum, magnesium, or titanium. The high specific modulus and the low thermal expansion (11.6 μm/m · K) translates into good physical stability and low distortion during inertial or thermal stressing, making beryllium useful for critical aerospace components. Its exceptionally good dimensional stability and ability to reflect infrared radiation makes beryllium highly suited for mirrors, either as polished or plated substrate. The near transparency of beryllium to x-rays and other high-energy electromagnetic radiation is responsible for its widespread use in foil gage as windows in x-ray tubes and radiation-detection devices.

Beryllium is an important alloying element in copper and nickel for producing commercially important age-hardening alloys that are used in electrical contacts, springs, spot welding electrodes, and nonsparking tools. It is also added to aluminum and magnesium for grain refinement and oxidation resistance.

Processing and Product Forms

While beryllium can be melted and cast, the resulting casting has coarse grains (>50 μm) that are difficult to process, and attempts to refine them by alloying have been largely unsuccessful. The fine grain size is produced primarily by powder metallurgy (P/M) techniques, from which it inherits the fine grain size (5 to 15 μm) from the powder processing. Powder consolidation is done by vacuum hot pressing and has also been done by hot isostatic pressing or cold isostatic pressing followed by vacuum sintering.

Consolidated beryllium shows only modest ductility ($\leq$3% tensile elongation) at room temperature, which is attributed to a large covalent component in its atomic bonding in the *c*-axis direction and to its hexagonal close-packed (hcp) crystal structure, which is limited at room temperature to only one slip direction on two crystal planes, basal and prism. This low ductility is not improved even when impurities are reduced to levels as low as $\sim$10 ppm. However, beryllium does show improved ductility at temperatures above 200 to 250 °C (392 to 482 °F), where more crystal deformation modes are available. At 400 °C (750 °F), for example, it shows a tensile elongation as high as 50%. Beryllium transforms to a body-centered cubic (bcc) phase at 1270 °C (2318 °F), only 13 °C below its melting point.

Beryllium is flat rolled, extruded into shapes, and forged at elevated temperatures. It is worked warm; the handbooks suggest a temperature range of 800 to 1100 °C (1470 to 2110 °F) for hot working. Beryllium is commercially available as tube shapes and as plate, sheet, and foil in thickness ranging from 0.013 to 15.2 mm (0.0005 to 0.6 in). Recrystallization annealing is done at 725 to 900 °C (1340 to 1650 °F). As with other hexagonal close-packed (hcp) metals, beryllium displays anisotropic mechanical properties in wrought forms because of crystallographic texture and grain morphology. The traditional ball-milling method of making powder produces flat, crystallographically oriented powder particles that naturally leads to a crystallographic texture in the initial pressing stage. Newer powder preparation techniques, involving impact-grinding or atomization methods, produce a more equiaxed product, avoiding the oriented flat powder produced by ball milling and reducing the amount of crystallographic texture during the initial consolidation operation. Even so, care is taken to fabricate beryllium with a fine grain and as random a crystallographic orientation as possible. The room-temperature tensile properties of cross-rolled sheet are 345 to 414 MPa (50 to 60 ksi) yield strength, 483 to 621 MPa (70 to 90 ksi) tensile strength, and 10 to 40% elongation. Both the tensile and the yield strength have been shown to obey the Hall-Petch relationship between yield strength and grain size.

Beryllium shows the machining characteristics of cast iron when the required carbide tools are used. It is commonly brazed and adhesive bonded and with care can be welded.

Beryllium Grades and Properties

Commercially available grades of beryllium are distinguished by impurity levels and BeO content. The metal, in fact, normally contains 0.7 to 4.25% of BeO, which is unavoidable and increases with the fineness of the beryllium powder used in the consolidation process. It has extremely low solubility for oxygen and readily forms oxide particles that are situated at grain boundaries, which help to control grain growth without being harmful to ductility below 1.2% BeO. Table 1 lists chemical compositions of commercial grades of beryllium.

Table 1 Chemistry of commercial grades of beryllium

Beryllium grade	Beryllium components, %		Maximum impurities, ppm					
	Be, min	**BeO, max**	**Al**	**C**	**Fe**	**Mg**	**Si**	**Other, each**
Structural grades								
S-65B	99.0	0.7	600	1000	800	600	600	400
S-200F and S-200FH	98.5	1.5	1000	1500	1300	800	600	400
Instrument grades								
I-70A	99.0	0.7	700	700	1000	700	700	400
O-50	99.0	0.5	700	700	1000	700	700	400
I-220B	98.0	2.2	1000	1500	1500	800	800	400

Of the structural grades (indicated by the S in the designation), S-65B, with 99.0% min Be and 0.7% BeO, offers the most ductility at room temperature: 207 MPa (30 ksi) yield strength, 290 MPa (42 ksi) tensile strength, and 3% min elongation. Grade S-200F, with 98.5% min Be and 1.5% BeO is stronger, but less ductile, at room temperature: 240 MPa (35 ksi) yield strength, 325 MPa (47 ksi) tensile strength, and 2.0% elongation. This grade has usable strength and modulus up to 600 to 650 °C (1110 to 1200 °F), at which temperature the tensile properties are 100 MPa (15 ksi) yield strength, 130 MPa (19 ksi) tensile strength, and 10% elongation.

Instrument and Optical Grades. Instrument grades, indicated by the I in the designations I-220B and I-400A, are used for inertial-guidance systems where high geometrical precision and resistance to plastic deformation on a part-per-million scale (microyield strength) are required. In addition to these grades, I-70 was developed for optical components in satellite imaging systems and optical grade O-50 was developed for infrared optical instruments. Table 1 gives compositions of instrument/optical grades.

Beryllium Alloys. Beryllium is too reactive to accept alloying elements; it reacts to form stable compounds with most of the other common metals. Most of the research into beryllium-base alloys has been conducted on the beryllium-aluminum system. One alloy that has achieved limited commercial success is Lockalloy (62Be-38Al). This alloy, which has a density of 2.1 g/cm^3 (0.076 lb/in.^{3}) and an elastic modulus of 200 GPa (29×10^6 psi), has been used in avionics (thermal management) systems, automotive components (brake calipers in race cars), and aircraft and satellite structures. When compared to unalloyed beryllium, beryllium-aluminum alloys offer improved ductility (5 to 7% elongation), yield strength (275 to 310 MPa, or 40 to 45 ksi), and tensile strength 380 MPa, or 55 ksi).

Corrosion Resistance. Beryllium forms a thin protective oxide (BeO) coating that provides good corrosion resistance to the atmosphere at room temperature and giving it excellent resistance to pure water up to 300 °C (570 °F). However, corrosion resistance is impaired by impurities. The presence of carbides or chlorides, in particular, can cause a reaction with moist air at room temperature. Above 760 °C (1400 °F), beryllium reacts with oxygen and nitrogen, but not at all with hydrogen at any temperature. It is attacked by many dilute common acids at room temperature. It can be anodized or chromate coated for improved corrosion resistance.

Health and Safety Considerations. The main concern associated with handling beryllium is the effect on the lungs when excessive amounts of respirable beryllium powder or dust are inhaled. Sensitive individuals exposed to airborne beryllium may develop the lung disease berylliosis. Users should comply with occupational safety and health standards applicable to beryllium in Title 29, Part 1910, Code of Federal Regulations.

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Very High Density Metals

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Introduction

VERY HIGH DENSITY METALS are used for applications such as counterweights, radiation shields, and armor-piercing, kinetic-energy penetrators. Though lead is often thought of as the prototype high-density metal, its softness and low melting temperature make it inappropriate for many applications. In addition, the density of lead is substantially lower than numerous other metals, as shown in Table 1. Of these higher-density alternatives, only depleted uranium, tungsten, and tantalum are practical for most commercial applications. Tantalum is discussed in the Section "Refractory Metals and Alloys" in this Handbook. The remainder of this section will discuss the most commonly used very high density materials: depleted uranium and tungsten alloys.

Table 1 Metals with densities >40% greater than lead

Metal	Density, g/cm^3
Tantalum	16.6
Plutonium	19.0-19.7
Uranium	19.1
Tungsten	19.3
Precious metals (gold, platinum, rhenium)	19.3-19.7

Density of lead = 11.35 g/cm^3

Depleted Uranium and Uranium Alloys

Metallurgy. Naturally occurring uranium makes up 0.0004% of the crust of the Earth; it is 40 times more plentiful than silver, and 800 times more plentiful than gold. Natural uranium contains approximately 0.7% fissionable U^{235} and 99.3% U^{238}. Isotopic separation is done during chemical processing of uranium ores, resulting in enriched UF_6, which contains much more than 0.7% U^{235} and is reserved for nuclear applications, and depleted UF_6, which is typically 99.8% U^{238} and is available for nonnuclear applications requiring very high density.

Uranium metal is produced by hydrogen reduction of UF_6 to UF_4, followed by high-temperature reaction of UF_4 with magnesium or calcium to produce uranium derbies. These derbies are vacuum induction remelted, during which alloying elements can be added and poured into either castings of the desired shape or ingots for subsequent metalworking. The ingots are then formed by hot working processes such as rolling, forging, or extrusion, sometimes followed by secondary warm or cold rolling or swaging. Cast or wrought uranium parts exhibit typical metallic strength and ductility. They can be machined by conventional methods and welded by inert atmosphere processes. They are very prone to oxidation and corrosion, so protective coatings or alloying is frequently used to minimize environmental degradation.

Unalloyed uranium exhibits three polymorphic forms: γ phase (body-centered cubic, or bcc) above 771 °C (1420 °F), β phase (tetragonal) between 665 and 771 °C (1229 and 1420 °F), and α phase (orthorhombic) below 665 °C (1229 °F). The high-temperature γ phase is very soft and ductile, and dynamic recrystallization occurs when it is plastically deformed. However, metalworking in the γ range is usually avoided because rapid oxidation results in poor surface quality. The intermediate-temperature β phase is brittle and unsuitable for metalworking processes. The α phase deforms primarily by slip at temperatures above approximately 200 °C (390 °F), but increasing amounts of twinning occur as temperature decreases below that level. The combination of low-flow stress, high ductility, and reduced oxidation rate makes the high-α range ideal for primary hot working. Dynamic recrystallization occurs above approximately 550 °C (1020 °F), but the material work hardens if deformation is continued as the ingot cools to lower temperatures. Below approximately 200 °C (390 °F) the material becomes much stiffer, but secondary rolling and swaging can be done as low as room temperature if periodic recrystallization annealing at about 600 °C (1110 °F) is performed.

The mechanical properties of unalloyed uranium vary substantially with processing history, as shown in Table 2. As-cast uranium typically exhibits very large grains ($\sim$1 mm or more). These frequently result in nonuniform localized deformation and cause tensile ductility to be low and varied. Heat treating in the β-phase field is often used to refine the α grain structure and to increase ductility. When done in a vacuum, high-α or -β heat treatment also removes embrittling hydrogen from the material, thus further increasing ductility. Alpha-worked and recrystallized uranium contains much finer grains and exhibits substantially higher ductility. Maximum ductility is obtained in warm-finished wrought material. Alpha-uranium exhibits a ductile-to-brittle transition in the vicinity of room temperature. The presence of even very small amounts of dissolved hydrogen (fractional parts per million) increases the ductile-to-brittle transition temperature. Warm working makes the material more tolerant to hydrogen (perhaps by providing dislocation hydrogen sinks), thus suppressing the ductile-to-brittle transition and increasing room-temperature ductility.

Table 2 Properties and applications of uranium and uranium alloys

Alloy	Density, g/cm^3	Processing	Hardness	Yield strength		Tensile strength		Elongation[a], %	Corrosion resistance	Used for applications requiring	Precautions, comments
				MPa	**ksi**	**MPa**	**ksi**				
Unalloyed	19.1	As cast	93 HRB	205	30	450	65	6	Poor	Complex shapes, minimum strength and ductility	. . .
	19.1	Cast, b-quenched[a], H-outgassed[b],	93 HRB	295	45	700	100	22	Poor ductility	Complex shapes, improved	. . .
	19.1	α-rolled[c],	94 HRB	270	40	575	85	12	Poor	Sheet, rod, etc., minimum strength and ductility	. . .
	19.1	α-rolled[c], H-outgassed[b]	94 HRB	270	40	720	105	31	Poor	Sheet, rod, etc., improved ductility	. . .
	19.1	Warm rolled[d]	94 HRB	220	30	750	110	49	Poor	Sheet, rod, etc., maximum ductility	. . .
U-2Mo	18.6	γ-annealed[e]	. . .	415	60	830	120	10	Poor	Improved strength	. . .
U-0.75Ti	18.6	γ-	42 HRC	965	140	1656	225	19	Fair	Combined	Section

		quenched(f), aged at 380 °C (715 °F)(g)								high strength and ductility	thickness limitations, high residual stresses, sensitive to hydrogen and moisture
	18.6	γ-quenched(f), aged at 450 °C (840 °F)(g)	52 HRC	1215	175	1660	240	<2	Fair	Maximum hardness	High residual stresses, prone to delayed cracking
U-6Nb	17.3	γ-quenched(f)(h)	82 HRB	160	25	825	120	31	Excellent	Corrosion resistance, high ductility	Correctly reduced section thickness limitations
U-10Mo	16.4	γ-quenched(f)	28 HRC	900	130	930	135	9	Excellent	Corrosion resistance, high strength	Minimal section thickness limitations, prone to stress corrosion

(a) Quenched from 720 °C (1330 °F), reheated to 600 °C (1110 °F), slow cooled; this sequence is often done twice.

(b) Vacuum heat treated in high-α region; time depends on section thickness.

(c) Heated in molten salt to 640 °C (1185 °F), then rolled. Dynamic recrystallization occurs above 550 °C (1020 °F); hardness and strength increase if rolling temperature drops below 550 °C (1020 °F).

(d) Several sequences of rolling at ~300 °C (570 °F) plus vacuum annealing at 600 °C (1110 °F); final anneal at 550 °C (1020 °F).

(e) Heat treated for 1h at 800 °C (1470 °F) in vacuum (longer if required for removing hydrogen from thick sections), slow cooled.

(f) Heat treated for 1 h at 800 °C (1470 °F) in vacuum (longer if required for removing hydrogen from thick sections), quenched in water or oil (rate depends on section thickness).

(g) Age 5 h in vacuum or dry argon.

(h) Heat treated for 1h at 800 °C (1470 °F) in vacuum, critical quench rate much lower than required for U-0.75Ti; air cool usually sufficient for U-10Mo, but not for U-6Nb.

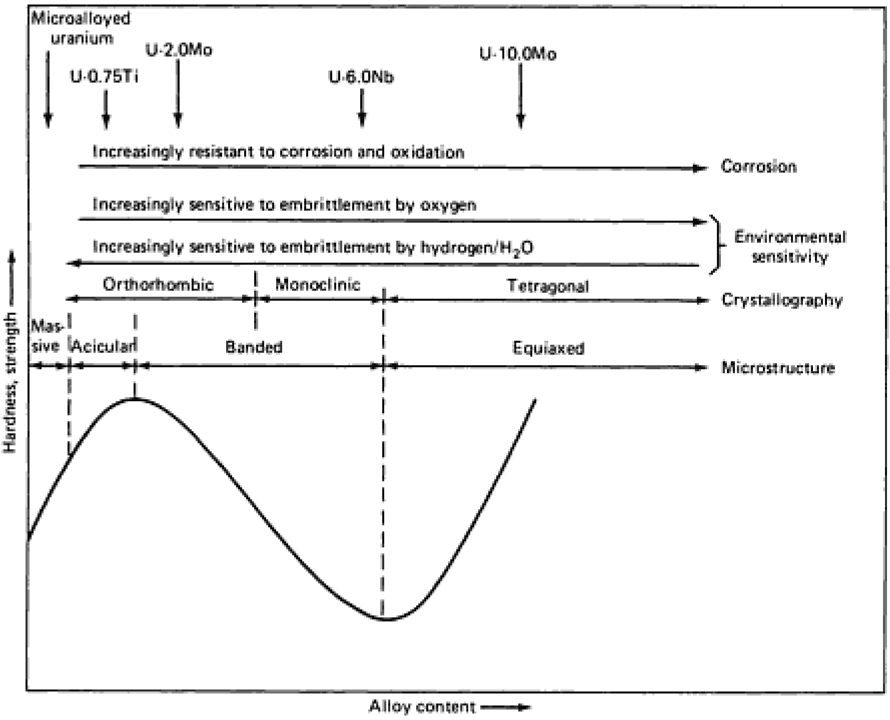
Processing and Properties. Uranium is often alloyed to improve its corrosion resistance and mechanical properties. Alloying elements such as titanium, niobium, molybdenum, zirconium, and vanadium are extensively soluble in the high-temperature phase, much less soluble in the intermediate-temperature β phase, and essentially insoluble in the low-temperature α phase. Titanium is used primarily to increase strength. Niobium produces the greatest increases in oxidation and corrosion resistance. Small amounts of vanadium can be used to refine α grain size in castings.

Uranium alloys are typically vacuum induction melted, cast, and fabricated by the same method as unalloyed uranium. The primary exceptions to this are alloys that contain significant amounts of high-melting-temperature niobium; these are frequently vacuum arc melted. Some highly alloyed materials, such as U-6Nb, must also be worked in the γ temperature range.

Virtually all uranium alloys are vacuum solution treated in the γ range (~800 to 850 °C, or 1470 to 1560 °F) to dissolve the alloying elements and remove hydrogen. The resulting microstructures and properties are strongly influenced by cooling rate from the solution treatment temperature.

Slowly cooled alloys exhibit two-phase microstructures in which the alloying elements are present in the second phases. These second phases are typically intermetallic compounds or alloy-stabilized variations of the γ phase. The second phases increase strength and decrease ductility in the same way that addition of carbon to iron results in strengthening via the formation of increasing amounts of Fe_3C. Because the alloying additions are not in solid solution in the uranium, they have little beneficial effect on oxidation and corrosion resistance.

When alloys are quenched, the equilibrium phase transformations are frequently suppressed, resulting in a variety of nonequilibrium microstructures that are supersaturated with alloying elements and exhibit a wide range of useful properties. Three effects are particularly important. First, because the alloying elements remain in solid solution in the uranium, quenched materials exhibit increased resistance to corrosion and oxidation. In addition, the alloying elements provide solid-solution strengthening. Finally, because these solid solutions are supersaturated, they can be age hardened by subsequent lower-temperature heat treatment. Figure 1 shows how microstructure and properties of as-quenched alloys change with increasing alloy content.



Microalloyed uranium
U-0.75Ti
U-2.0Mo
U-6.0Nb
U-10.0Mo
Increasingly resistant to corrosion and oxidation
Corrosion
Increasingly sensitive to embrittlement by oxygen
Increasingly sensitive to embrittlement by hydrogen/H₂O
Environmental sensitivity
Orthorhombic
Monoclinic
Tetragonal
Crystallography
Mas-sive
Acicular
Banded
Equiaxed
Microstructure
Hardness, strength
Alloy content

Fig. 1 Effects of composition on structure and properties of quenched uranium alloys

Very dilute alloys (<0.3% alloying addition) typically undergo the equilibrium sequence of phase changes, but the alloying elements tend to retard these diffusional transformations, enabling them to be suppressed to lower temperatures. This can be exploited to reduce α grain size in castings, particularly via the use of small vanadium additions. U-0.2V castings that are isothermally transformed from β to α at approximately 516 °C (961 °F) exhibit grain sizes 10 to 20 times finer than those in unalloyed uranium castings.

In more concentrated alloys (with alloying additions of 0.5% to several percent), the equilibrium sequence of phase changes can be completely avoided by quenching; the γ phase then undergoes diffusionless martensitic transformation to a variety of supersaturated variations of the α phase. In very highly alloyed uranium (approaching 10% alloying addition), the martensite start (M_s) temperatures are below room temperature, so metastable variations of the high-temperature γ phase are retained.

The critical cooling rates needed to avoid diffusional transformations and obtain these supersaturated structures vary in a complex manner with alloy content. In general, however, dilute alloys such as U-0.75Ti require rapid quenching. This restricts the section thicknesses in which they can be used. More concentrated alloys, such as U-6Nb and U-10Mo, require much less severe quenching and thus can be processed in larger sections.

Uranium alloys are susceptible to environmental cracking in ionic chloride and other environments. Dilute alloys are also sensitive to hydrogen, which is readily generated by surface decomposition of atmospheric moisture. Concentrated alloys are more sensitive to atmospheric oxygen. The tensile surface residual stresses that result from quenching of complex-shape parts can be sufficient to cause cracking in these relatively mild environments. The magnitudes of these stresses are limited by the yield strengths of the as-quenched material. Hence, high-strength alloys, such as U-0.75Ti and U-10Mo, tend to be most susceptible to delayed cracking, while low-strength alloys such as U-6Nb are relatively immune.

General oxidation and corrosion resistance increase with increasing the amount of alloy in solid solution. As a result, alloys such as U-6Nb and U-10Mo are often used in applications that require good corrosion resistance.

All previously quenched materials are amenable to subsequent aging. Age hardening occurs at temperatures up to approximately 450 °C (840 °F). This significantly increases strength and decreases ductility. Age-hardened U-0.75Ti is the alloy most commonly selected for applications requiring high strength, but others can also be strengthened in this way. Age-hardened materials retain their enhanced corrosion resistance, as most of the alloying additions remain in solid solution. Residual stresses introduced during the prior quench are also progressively relieved as age hardening progresses.

Overaging occurs by cellular decomposition of the supersaturated solutions at temperatures greater than approximately 450 °C (840 °F). This results in substantially decreased strength. Ductility increases in some cases, but not in others (notably U-0.75Ti) as semicontinuous films of brittle intermetallic develop. Corrosion resistance also decreases dramatically, as the alloying additions are no longer retained in solid solution.

Machining, Welding, and Corrosion Protection. Uranium and uranium alloys can be machined by conventional methods and are roughly as machinable as stainless steels. Very soft materials, such as unalloyed uranium and as-quenched U-6Nb, tend to be gummy. Aged materials, such as U-0.75Ti, are somewhat difficult because of their high hardness. Machining is easiest with alloys that have been slowly cooled or overaged to produce relatively soft two-phase microstructures.

Uranium and uranium alloys are inherently weldable by inert atmosphere processes, but subcritical cooling and residual stress development cause difficulties in some composition ranges. U-0.75Ti is difficult to weld because weld cooling rates cause subcritical cooling from the γ phase, resulting in brittle microstructures. U-6Nb is readily weldable because it is much less quench-rate sensitive and because its low as-quenched strength prevents the development of high weld-induced residual stresses. U-10Mo is free from quench-rate sensitivity concerns, but its higher strength permits higher residual stresses to develop, thus increasing susceptibility to delayed cracking.

Uranium and dilute uranium alloys are highly susceptible to oxidation and corrosion. Protective coatings, such as electroplated nickel or ion-plated aluminum, are frequently applied to minimize such environmental effects. More concentrated alloys, such as U-6Nb and U-10Mo, are more resistant to oxidation and corrosion, and thus usually are not coated.

Design Considerations and Applications. Several design limitations must be considered in applications of depleted uranium and uranium alloys: susceptibility to oxidation and corrosion, relatively low toughness (particularly at low temperatures), and health and safety considerations associated with processing and use.

Unalloyed uranium is used primarily for radiation shielding, counterweights, and other applications with minimal strength requirements. Nickel electroplating or aluminum ion plating is used to provide corrosion protection where needed. U-0.75Ti is frequently chosen for applications requiring high strength and moderate toughness, such as kinetic-energy penetrators. Quench-rate sensitivity limits the use of this alloy in diameters greater than 30 or 40 mm (1.2 or 1.6 in.). U-6Nb is most frequently used in applications requiring high ductility and inherent resistance to oxidation and corrosion.

Health and Safety Considerations. Several health and safety issues must be taken into account when working with depleted uranium. First, finely divided material is pyrophoric. Liberal amounts of machining fluid must be used, and machining chips, saw fines, and grinding residue must be removed frequently from tools and stored submerged in water or oil. Second, heavy-metal poisoning can result if this material is inhaled or ingested. Depleted uranium is roughly as toxic as other heavy metals, such as lead. Inhalation and ingestion are best avoided by avoiding dry grinding where fine airborne particulates could be generated, by cleaning work areas periodically (especially where saw fines or grinding residue is generated or where oxide flakes off during hot working operations), and by applying good personal hygiene practices in uranium work areas. Finally, depleted uranium is mildly radioactive. This low level of radioactivity is generally considered to constitute less of a hazard than chemical toxicity. Working in the vicinity of depleted uranium and normal handling of this material do not result in exposures that exceed current standards. Nonetheless, unnecessarily close contact (such as carrying depleted uranium around in a pocket) should be avoided.

Public perception sometimes exaggerates these legitimate health and safety issues far beyond what seems technically justified. Such public concern over the radioactivity of depleted uranium has created an environment that is increasingly hostile to its use and is forcing serious consideration of other alternatives, such as tungsten heavy alloys.

Tungsten and Tungsten Heavy Alloys

Metallurgy and Applications. While often considered an uncommon metal, tungsten makes up approximately 0.0069% of the earth's crust, roughly the same as copper. The primary ores--scheelite and wolframite--are typically pulverized and concentrated by flotation. The ore concentrate is then digested and reacted in several steps to form ammonium paratungstate (APT). This is calcined to form blue oxide ($WO_{\sim 2.8}$), which is then reduced to metallic tungsten via hydrogen reduction.

Because of the extremely high melting point (3410 °C, or 6170 °F) of tungsten, virtually all commercial production of bulk shapes is done via powder metallurgy. For making tungsten rod stock, metallic powder is compacted at pressures typically between 150 and 600 MPa (20 and 85 ksi) to form a long billet. Following a light H_2 presinter, the green billet is clamped into water-cooled electrodes for direct sintering in H_2. Currents exceeding 1350 A/cm^2 of the initial cross section are commonly required for adequate ohmic heating. Even at temperatures exceeding 3000 °C (5430 °F), full densification does not occur. This is accomplished by subsequent thermomechanical processing (hot swaging and reannealing), during which the stock is reduced to the required diameter. The final deformation step is typically accomplished by hot drawing to provide the desired surface finish.

Tungsten has a bcc crystal structure and is the only elastically isotropic metal known. The Young's modulus of tungsten is approximately 410 GPa (60 psi $\times 10^6$), among the highest of all metals. Bulk tungsten exhibits a ductile-to-brittle transition in the range of 200 to 500 °C (390 to 930 °F), depending on processing history. As a result, it must be worked warm to avoid cracking. Heavily worked tungsten develops a more ductile fibrous microstructure, capable of being bent into tight radii without fracture. The strengths of small-diameter filaments can approach 4.1 GPa (590 ksi).

If heavily deformed tungsten is exposed to temperatures of approximately 1200 °C (2190 °F) or greater for sufficient time, recrystallization and segregation of dissolved impurities to grain boundaries occur, resulting in a return of brittle behavior. This is the principal reason that tungsten is generally considered nonweldable; cracking occurs in the fusion and heat-affected zones. When it is necessary to join tungsten to itself or other metals, mechanical fastening should be considered.

For specialized applications, a number of other alternative technologies exist for forming bulk tungsten shapes: arc melting and casting (sometimes using the skull approach), electron beam melting, chemical vapor deposition, and plasma spraying. Arc casting is often used for components requiring very high purity levels. Plasma spraying is currently utilized for the fabrication of axisymmetric thin-wall parts.

Tungsten provides the materials designer with the highest density of any nonradioactive, nonprecious metal. The extremely high melting point of tungsten also makes it the material of choice for incandescent lamp filaments, high-current electrical contacts, and electrodes for arc lamps and tungsten inert gas welding (also called gas tungsten arc welding, or GTAW). While pure tungsten can be used for all these cited applications, optimum performance is generally realized in doped, alloyed, or composited forms.

Lamp filaments are "AKS" doped with aluminum potassium silicate. This results in potassium bubble formation on grain boundaries, thereby promoting highly interlocking grains and extending useful filament life. Filaments intended for use in high-vibration or shock service contain 1 wt% dispersed thoria, providing boundary pinning points and enhanced high-temperature strength.

Electrical contacts are typically made from tungsten-copper or tungsten-silver composites formed by infiltration. The W-10Cu composite provides an excellent coefficient of thermal expansion match (6.5×10^{-6}/K) with major semiconductor packaging materials and thus is widely used as a high-dissipation, heat-sink material. Low expansion is derived from the tungsten phase, thermal conductivity is derived from the copper phase.

High-intensity, direct-current arc lamps typically utilize tungsten anodes and cathodes containing at least 1 wt% thoria for enhanced thermionic emission and minimization of recrystallization. Electrodes for GTAW likewise contain rare-earth oxides for greater emission, providing improved arc stability and extended life.

Tungsten Heavy Alloy Processing and Properties. Tungsten heavy alloys (WHAs) offer a number of advantages over the pure metal for inertial masses and for density-related applications such as radiation shielding. These alloys typically consist of 90 to 98 wt% W in a matrix consisting of nickel, iron, and/or cobalt. While slightly less dense than pure tungsten, WHAs can be readily fabricated into large, full-density components via liquid phase sintering (LPS) in H_2 at temperatures of 1470 to 1580 °C (2680 to 2875 °F)--far below the temperature required to process the pure metal. In addition, virtually all WHAs are readily machinable, allowing the fabrication of complex geometries using common metalworking tools and techniques.

Tungsten heavy alloys are generally ductile, but are susceptible to hydrogen embrittlement by nature of the bcc structure of the principal phase. Consequently, hydrogen removal by vacuum annealing or other means will result in increased quasi-static ductility. Further processing by resolutionization and water quenching locks interstitial impurities in wider distribution for reduced segregation-induced embrittlement, thereby substantially improving fracture toughness.

While hot isostatic pressing and rapid consolidation techniques are applicable, WHAs are most commonly consolidated to full density by solid-state sintering or by liquid phase sintering (LPS). The former process is ideal for parts that require minimal thermal distortion and minimal mechanical properties. Liquid phase sintering provides a superior means of obtaining full density and improved mechanical properties, but much greater distortion ("slumping") occurs during LPS due to capillary action and/or gravity. The LPS process results in a microstructure consisting of spheroids (approximately 40 to 60 μm in size) of nearly pure tungsten in an austenitic binder phase of transition metals plus dissolved tungsten, as shown in Fig. 2. This provides better mechanical properties due to less angular grains, lower tungsten-tungsten contiguity, and a greater percentage of metastable tungsten in the solid-solution binder. Tungsten-tungsten contact and interfacial embrittlement are the principal factors limiting mechanical properties of WHAs.

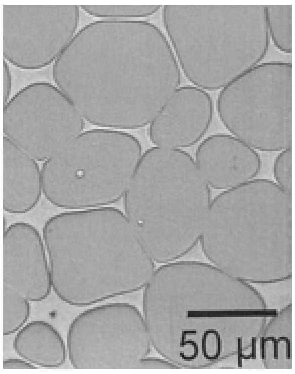


Fig. 2 Typical microstructure of W-7Ni-3Fe heavy alloy consolidated by liquid phase sintering

The W-Ni-Cu system was the first heavy-alloy system developed and is still used occasionally for components that must exhibit minimal ferromagnetic character. By far the most important alloy system commercially is the W-Ni-Fe ternary. This family of alloys has been used for the full range of WHA applications, having higher mechanical properties than the earlier tungsten-nickel-copper alloys. Binder composition is important in that it strongly influences mechanical properties and determines which, if any, postsinter heat treatments will be needed. Nickel-iron ratios in the range of 2 to 4 are most common, as material in this range can be safely processed without concern for intermetallic precipitation in the binder and consequent embrittlement. Below a nickel-iron ratio of approximately 1.2, there is a risk of forming Fe_7W_6 (a μ-phase), depending on the time/temperature profile employed. Once formed, its thermochemical stability prevents its resolution at all practical processing temperatures.

Exceeding a nickel-iron ratio of $\sim$5 typically leads to Ni_4W precipitation for average sintering and cooling cycles. Unlike the iron-rich intermetallic, this nickel-rich compound can be readily resolutionized at approximately 1150 °C (2100 °F), making WHAs with higher nickel-iron ratios practical to process. Tungsten heavy alloys with nickel-iron ratios ranging from 6 to approximately 15 provide noticeably higher properties, but require both vacuum annealing and resolutionization/quenching. All WHAs will benefit from resolutionization/quenching even if not required by composition for intermetallic control, as this procedure reduces the extent of segregation-induced embrittlement at interfaces caused by interstitials such as carbon, sulfur, and phosphorus, thereby enhancing alloy toughness.

For certain applications, the strength and hardness of unworked material are insufficient. While alternative methods of increasing strength are available (e.g., alloying with molybdenum), WHAs are most commonly swaged, extruded, forged, or upset to enhance strength and hardness (Table 3). Thus, there is a continuous set of mechanical properties available via the trade-off in ductility and toughness for strength and hardness. The greater the initial unworked property set, the greater the range of processing options.

Table 3 Typical properties for the tungsten heavy alloy W-4.9Ni-2.1Fe

Condition	Ultimate tensile strength		Elongation, %	Hardness, HRC	Charpy toughness, J
	MPa	**ksi**			
As sintered	860	125	15	29	. . .
Vacuum annealed	910	130	25	29	. . .
Quenched	930	135	32	29	230
Swaged (15% RA)	1115	160	16	39	150
Swaged (25% RA)	1200	175	14	40	110
Swaged (25% RA) + aged 1 h at 500 °C (930 °F)	1400	205	7	44	80

In response to the need for ever higher mechanical properties for heavy alloys (driven primarily by gun-fired, kinetic-energy penetrator requirements), the W-Ni-Co family of alloys was developed in the 1980s. Though requiring postsinter heat treatment, they can provide clearly superior mechanical properties (Table 4).

Table 4 Property comparison of unworked tungsten heavy alloys

Alloy	Ultimate tensile strength		Elongation, %	Hardness, HRC	Charpy toughness, J
	MPa	**ksi**			
W-6.3Ni-2.7Fe	940	135	35	29	300

WHA Design Considerations and Applications. The composite nature of the WHA microstructure carries several implications. Perhaps foremost is the mechanical consideration of notch sensitivity. Ideally, practical designs should not contain notches, threads, or corners with radii smaller than approximately 0.5 mm (0.2 in.). Otherwise, stress concentration will reduce mechanical strength. Though WHAs are not particularly susceptible, corrosion can nevertheless occur due to local galvanic activity between the tungsten phase and the electrochemically dissimilar austenitic binder phase if a suitable electrolyte is present. Highly alkaline solutions readily attack the tungsten phase. The mechanical mismatch of the composite structure also directly influences formability limits for metalworking operations. However, the elastic mismatch does serve to attenuate vibration--a valuable factor for high-stiffness, low-chatter WHA boring bars and tool holders.

Due to differences in both chemistry and melting point of the tungsten phase and the binder, WHAs are not readily weldable. Mechanical fastening should be employed whenever possible. Brazing of WHAs to dissimilar metals is possible, but the strength of the joint is typically low due to localized formation of embrittling intermetallics.

Tungsten heavy alloys are used in an increasingly wide array of products, including such diverse end uses as radiation collimation and shielding, balancing weights in aircraft and golf clubs, lead-free waterfowl shot, high-stiffness (modulus of ~380 GPa, or 55 psi × 10^6) boring bars and tooling, kinetic-energy penetrators, gyroscope components, and vibration damping in disk-drive heads. These alloys are an ideal choice for applications requiring a combination of good machinability, high density, excellent thermal stability, moderate cost, and/or freedom from the toxicity considerations of lead and depleted uranium-base materials. As environmental and safety considerations become even more important drivers in the planning of new products and applications, the fact that WHAs have only a slight percentage of their total weight in slightly toxic metals such as nickel and cobalt provides an incentive for their selection.

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Materials for Sliding Bearings

Introduction

A SLIDING BEARING (plain bearing) is a machine element designed to transmit loads or reaction forces to a shaft that rotates relative to the bearing. Journal bearings are cylindrical (full cylinders or segments of cylinders) and are used when the load or reaction force is essentially radial (that is, perpendicular to the axis of the shaft). Thrust bearings are ring shaped (full rings or segments of rings) and are used when the load or reaction force is parallel to the direction of the shaft axis. Both radial and axial loads can be accommodated by flange bearings, which are journal bearings constructed with one or two integral thrust bearing surfaces. The sliding movement of the shaft surface or thrust-collar surface relative to the bearing surface is characteristic of all plain bearings. In many applications, plain bearings offer advantages over rolling-contact bearings--such as lower cost, smaller space requirements, the ability to operate with marginal lubricants, resistance to corrosion, and the ability to sustain high specific loads.

Classifications

Sliding bearings are commonly classified by terms that describe their application, such as:

- Connecting-rod bearing
- Main bearing
- Camshaft bearing or bushing
- Electric motor shaft bushing
- Countershaft thrust washer

The terms "bearing" and "bushing" are used interchangeably and do not have meanings that are significantly different in terms of function or location in a machine.

With respect to size, sliding bearings are frequently classified as either thin wall (that is, thinner than ~5 mm, or 0.2 in.) or heavy wall. In general, bearings with diameters >150 mm (>6 in.) are considered to be in the heavy-wall class. Configurations can be further described as half round, full round, flanged, or washer. The Society of Automotive Engineers (SAE) standards classify thin-wall bearings into three groups: sleeve-type half bearings, split-type bushings, and thrust washers.

Sliding bearings are also frequently classified according to material construction, as single-metal (solid), bimetal (two-layer), or trimetal (three-layer) bearings. These terms refer to the number of principal functional layers that are used. Each one of these types of construction is in widespread commercial use and in a wide variety of applications. The use of two or three separate layers provides a means for developing property combinations that cannot be obtained with single-metal bearings.

Design and Selection

Wear Damage Mechanisms

From the standpoint of bearing material design and selection, some or all of the following wear damage mechanisms must be considered:

- Surface fatigue wear
- Abrasive wear
- Adhesive wear
- Erosive wear
- Corrosion

The potential for wear damage is intimately linked to interactions among operating system characteristics that include:

- Magnitude of bearing loads
- Nature of load (cyclic or steady, unidirectional, or reversing)
- Speeds
- Lubricants and lubrication system characteristics
- Lubricant cleanliness and filtration
- Operating temperatures
- Counterface (shaft) material and finish
- Alignment and rigidity
- Life expectancy

More detailed information is available in articles describing sliding bearings in Volume 11, *Failure Analysis and Prevention,* and Volume 18, *Friction, Lubrication, and Wear Technology,* of the *ASM Handbook.*

Properties of Bearing Materials

Surface and Bulk Properties. The conditions under which plain bearings must operate and the wide ranges over which these conditions can vary lead to concern about two kinds of bearing material properties: surface properties (those associated with the bearing surface and immediate subsurface layers) and bulk properties.

Conventional engineering definitions of material properties do not adequately describe the distinctive properties that are needed in materials for sliding bearings. Although there is no universally accepted system, of nomenclature, measurement or testing for these properties, they can be defined and studied in terms of the following characteristics:

- *Compatibility:* the antiwelding and antiscoring characteristics of a bearing material when operated with a given mating material
- *Conformability:* the ability of a material to yield to and compensate for slight misalignment and to conform to variations in the shape of the shaft or of the bearing-housing bore
- *Embeddability:* the ability of a material to embed dirt or foreign particles and thus prevent them from scoring and wearing shaft and bearing surfaces
- *Load capacity:* the maximum unit pressure under which a material can operate without excessive friction, wear, and fatigue damage
- *Fatigue strength:* the ability of a material to function under cyclic loading below its elastic limit without developing cracks or surface pits
- *Corrosion resistance:* the ability of a material to withstand chemical attack by uninhibited or contaminated lubricating oils
- *Hardness:* the ability to resist plastic flow under high unit compressive loads, conventionally measured by indentation hardness testing
- *Strength:* the ability to resist elastic and plastic deformation under load, conventionally measured by compression, shear, and tensile testing

Table 1 lists some of the more important relationships between bearing material properties and wear damage mechanisms. Compatibility can be regarded as a purely surface characteristic. Conformability and embeddability involve the surface and immediate subsurface and are strongly related to the bulk properties of strength and hardness. The other characteristics relate principally to bulk properties.

Table 1 Influence of bearing material properties on wear damage mechanisms

Bearing material property	Damage mechanisms counteracted	Causes
Compatibility	Adhesive wear	Asperity contact, surface roughness, inadequate oil film
Conformability	Adhesive wear, surface fatigue wear	Misalignment, edge loading, faulty assembly, geometric errors
Embeddability	Abrasive wear, adhesive wear	Dirt particles in oil, scoring
Fatigue strength	Surface fatigue wear	Excessive dynamic load, localized overload (for example, misalignment)
Hardness	Extrusion, erosive wear	Overheating, excessive load, cavitation effects
Corrosion resistance	Corrosive wear	Lubricant deterioration (overheating), lubricant contamination (water, fuel, refrigerant, combustion products)

Measurement and Testing. Of the six characteristics listed in Table 1, only hardness can be measured satisfactorily by standard laboratory test methods. Many special dynamic test rigs and test methods have been developed by the plain bearing industry to evaluate and to measure the other characteristics and their interactions. Most of these testing systems are designed to subject specimen bearings to operating conditions that are qualitatively similar to the conditions of intended service, but quantitatively more severe with respect to one or several parameters, such as: magnitude of load, surface speed, operating temperature, lubricant supply, and lubricant cleanliness.

Although much useful information has been developed through laboratory rig testing, it still is often necessary to test bearing materials and designs in full-size operating machines to clearly establish their overall suitability. Such testing is necessarily expensive and time consuming. It should be undertaken only after careful study both of the conditions under which the bearing will operate and of prior experience in similar applications.

Bearing Material Microstructures. All commercial significant bearing metals, with the exception of silver, are polyphase alloys. As indicated below, these polyphase alloys can be classified according to basic microstructural types.

- *Type I: Soft Matrix with Discrete Hard Particles.* Lead and tin babbitts are of this type.
- *Type II: Interlocked Soft and Hard Continuous Phases.* Many copper-lead and leaded bronze alloys are of this type.
- *Type III: Strong Matrix with Discrete Soft-Phase Pockets.* Low-lead bronzes and some aluminum-tin

alloys are of this type.

- *Mixed microstructures* that combine the characteristics of types I and III are exhibited by Al-Si-Sn alloys and Al-Si-Pb alloys.

Effects of Multilayer Construction. One of the most useful concepts in bearing material design came in 1941 with the recognition that the effective load capacities and fatigue strengths of lead and tin alloys are sharply increased when these alloys are used as thin layers intimately bonded to strong bearing backs of bronze or steel. Use is made of this principle (Fig. 1) in two-layer constructions using a surface layer of lead or tin alloy, usually no more than 0.13 min (0.005 in.) thick. Unimpaired compatibility is provided by such a layer, together with reasonably high levels of conformability and embeddability. Other useful compromises can be effected between surface and bulk properties by employing an intermediate copper or aluminum alloy layer between the surface alloy layer and a steel back. In these three-layer constructions, use of a surface layer thickness as low as 0.013 mm (0.0005 in.) offers even more favorable compromises between surface and bulk properties than are possible with two-layer constructions.

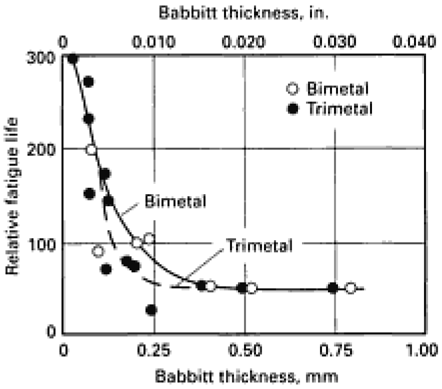

Fig. 1 Plot of bearing fatigue life versus thickness of a lead alloy babbitt surface layer as a function of the number of layers used. Bearing load, 14 MPa (2 ksi)

Heat and Temperature Effects. The reduced mechanical strength of bearing liner materials at elevated temperatures is an important consideration in the selection of a bearing material for a given application. Fatigue strength, compressive yield strength, and hardness decrease significantly with increased bearing operating temperature. Low-melting, lead-base, and tin-base bearing alloys are most severely limited in this respect, and copper alloys are limited the least. Aluminum alloys have high-temperature bearing properties intermediate to those of lead/tin and copper alloys (Fig. 2).

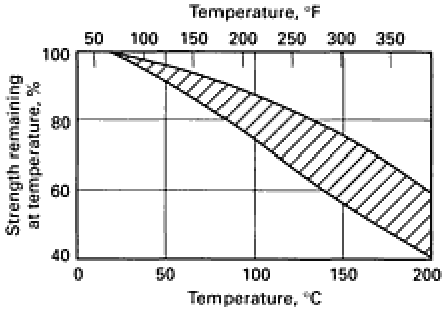

Fig. 2 Strength retention at elevated temperatures for aluminum-base bearing alloys

Bearing Material Systems

Because of the widely varying conditions under which bearings must operate, commercial bearing materials have evolved as specialized engineering materials systems rather, than as commodity products. They are used in relatively small tonnages and are produced by a relatively small number of manufacturers. Much proprietary technology is involved in alloy formulation and processing methods, the latter of which includes casting processes (strip, continuous, and centrifugal casting), powder metallurgy (continuous sintering, impregnation and infiltration, and powder rolling), and roll bonding. Successful selection of bearing material and/or processing methods for a specific application often requires close technical cooperation between the user and the bearing producer.

Single-Metal System

Most single-metal sliding bearings are made from either copper alloys or aluminum alloys. Some use is also made of cast zinc-base alloys, which serve as lower-cost substitutes for solid bronze.

Single-metal systems do not exhibit outstandingly good surface properties, and their tolerance of boundary and thin-film lubrication conditions is limited. As a result, the load capacity rating for a single-metal bearing usually is low relative to the fatigue strength of the material from which it was made. Because of their metallurgical simplicity, these materials are well suited for small-lot manufacturing from cast tubes or bars, using conventional machine shop processes.

Copper Alloys. Except for commercial bronze and low-lead tin bronze, copper alloys in single-metal systems are almost always used in cast form. This provides thick bearing walls (≥3.20 mm, or 0.125 in.) that are strong enough so that the bearing is retained in place when press fitted into the housing.

Commercial bronze and medium-lead tin bronze alloys C83420 and C83520 are used extensively in the form of wrought strip for thin-wall bushings, which are made in large volumes by high-speed press forming. The relatively poor compatibility of these alloys can be improved by embedding a graphite-resin paste in rolled or pressed-in indentations, so that the running surface of the bushing consists of interspersed areas of graphite and bronze. Such bushings are widely used in automotive engine starting motors.

The lead in leaded tin bronzes is present in the form of free lead that is dispersed throughout a copper-tin matrix so that the bearing surface consists of interspersed areas of lead and bronze. In general, the best selection of materials from this group for a given application will be the highest-lead composition that can be used without risking excessive wear, plastic deformation, or fatigue damage.

Aluminum Alloys. Virtually all solid aluminum bearings used in the United States are made from alloys containing from 5.5 to 7% Sn, plus smaller amounts of copper, nickel, silicon, and magnesium. Starting forms for bearing fabrication include cast tubes as well as rolled plate and strip, which can be press formed into half-round shapes. As is the case with solid bronze bearings, relatively thick bearing walls are employed in solid aluminum alloy bearings.

The tin in these alloys is present in the form of free tin that is dispersed throughout an aluminum matrix so that the bearing surfaces consist of interspersed areas of aluminum and tin. Surface properties are enhanced by the free tin in much the same way that those of bronze are improved by the presence of free lead.

The high thermal expansion of aluminum poses special problems in maintaining press fit and running clearances. Various methods are employed for increasing yield strength (for example, heat treatment and cold work) to overcome plastic flow and permanent deformation under service temperatures and loads.

Zinc Alloys. During the past 20 years, Zn-Al-Cu casting alloys have been used to replace cast bronze alloys in certain low-speed machinery bearing applications. These alloys do not contain any soft microconstituents that correspond to the lead used in bearing bronzes and to the tin in cast aluminum bearing alloys. To a considerable degree, compatibility of the zinc-base alloys seems to derive from their chemical behavior with hydrocarbon lubricants.

Porous Metal Bushings. Oil-impregnated porous metal bushings (self-lubricating bearings) can also be included in the single-metal systems category. The materials used for these bushings include unleaded and leaded tin-bronze, bronze-graphite, iron-carbon, iron-copper, and iron-bronze-graphite compositions.

Bimetal Systems

All bimetal systems employ a strong bearing back to which a softer, weaker, relatively thin layer of a bearing alloy is metallurgically bonded. Low-carbon steel is by far the most widely used bearing-back material, although alloy steels, bronzes, brasses, and (to a limited extent) aluminum alloys are also used. When steel bearing backs are employed, load-capacity ratings for both copper and aluminum alloys are sharply increased above those of the corresponding single metals without degrading any other properties.

Bronze-back materials do not exhibit combinations of performance characteristics substantially different from those of steel-back bearings. The practical advantages of bronze as a bearing-back material lie partly in the economics of small-lot manufacturing and partly in the relative ease with which worn bronze-back bearings can be salvaged by rebabbitting and remachining. From the standpoint of performance, the advantage of bronze over steel as a bearing-back material is the protection bronze affords against catastrophic bearing seizure in case of severe liner wear or fatigue. Similar protection is provided by using an aluminum alloy bearing back.

Although the surface properties of bronze bearing-back materials are not impressive, they are superior to those of steel, and these "reserve" bearing properties can be of considerable practical importance in large expensive machinery used in certain critical applications.

Trimetal Systems

Virtually all trimetal systems employ a steel bearing back, an intermediate layer of relatively high strength, and a tin alloy or lead alloy surface layer. Most of these systems are derived from steel-backed bimetal systems by the addition of a lead-base or tin-base surface layer.

The strengthening effects of thin-layer construction are notable in those systems that incorporate electroplated lead alloy surface layers $\leq$0.025 mm ($\leq$0.001 in.) thick. Comparison of fatigue strength and load capacity ratings of these systems with those of the corresponding bimetal systems shows that the thin lead alloy surface layer upgrades not only surface properties but also fatigue strength. The increase in fatigue strength can be attributed at least in part to the elimination of stress raisers, from which fatigue cracks can propagate.

Trimetal systems with electroplated lead-base surface layers and copper or aluminum alloy intermediate layers provide the best available combinations of cost, fatigue strength, and surface properties. Such bearings have high tolerances for boundary and thin-film lubrication conditions, and thus can be used under higher loads than can any of the bimetal systems.

Bearing Materials

Tin-Base Alloys

Tin-base bearing materials (babbitts) are alloys of tin, antimony, and copper that contain limited amounts of zinc, aluminum, arsenic, bismuth, and iron. The compositions of tin-base bearing alloys, according to ASTM B 23, SAE, and ISO specifications, are shown in Table 2.

Table 2 Designations and nominal composition of tin-base bearing alloys

Designation[(a)]			ASTM (B 23)	Composition, %				Product form	Applications
UNS	**SAE**	**ISO**		**Sn**	**Sb**	**Cu**	**Other**		
L13910	. . .	. . .	Alloy 1	91	4.5	4.5	. . .	Cast on steel or bronze back	Bimetal surface layer
L13870	. . .	. . .	Alloy 11	87	7	6	. . .	Cast on steel; bronze or steel-backed bronze	Bimetal and trimetal surface layer
L13890	Alloy 12	SnSb8Cu4	Alloy 2	89	7.5	3.5	. . .	Cast on steel; bronze or steel-backed bronze	Bimetal and trimetal surface layer
L13840	. . .	. . .	Alloy 3	84	8	8	. . .	Cast on steel or bronze back	Bimetal surface layer
. . .	. . .	SnSb12Cu6Pb	. . .	80	12	6	2 Pb	Cast on steel back	Bimetal surface layer

(a) UNS, unified numbering system; SAE, Society of Automotive Engineers; ISO, International Organization for Standardization; ASTM, American Society for Testing and Materials

The presence of zinc in these bearing metals generally is not favored. Arsenic increases resistance to deformation at all temperatures; zinc has a similar effect at 38 °C (100 °F) but causes little or no change at room temperature. Zinc has a marked effect on the microstructures of some of these alloys. Small quantities of aluminum (even <1%) will modify their microstructures. Bismuth is objectionable because, in combination with tin, it forms a eutectic that melts at 137 °C (279 °F). At temperatures above this eutectic, alloy strength is decreased appreciably.

Table 3 shows bulk mechanical properties of ASTM grades 1 to 3. These properties have some value for initial materials screening comparisons of alloys; but they are not reliable predictors of the performance of thin layers bonded to a strong backing, which is the manner in which tin-base babbitts are usually used in modem bearing practice. Layer thickness effects (Fig. 1) and temperature effects (Fig. 2) are more important practical considerations than the mechanical property differences among the various alloy compositions.

Table 3 Typical mechanical properties of chill cast tin-base bearing alloys

Designation				Compressive yield strength(a)				Ultimate tensile strength, 20 °C (68 °F)		Elongation, 20 °C (68 °F), %	Hardness, HB	
				20 °C (68 °F)		**100 °C (212 °F)**					**20 °C (68 °F)**	**100 °C (212 °F)**
UNS	**SAE**	**ISO**	**ASTM (B 23)**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**			
L13910	. . .	. . .	Alloy 1	30.3	4.40	18.3	2.65	64	9.3	2	17.0	8.0
L13890	Alloy 12	SnSb8Cu4	Alloy 2	42.1	6.10	20.7	3.00	77	11.2	. . .	24.5	12.0
L13840	. . .	. . .	Alloy 3	45.5	6.60	21.7	3.15	69(b)	10.0(b)	1(b)	27.0	14.5

(a) 0.125% offset.

(b) Values are for die-cast alloy specimens.

Compared with most other bearing materials, tin alloys have low resistance to fatigue, but their strength is sufficient to warrant their use under low-load conditions. These alloys are commercially easy to bond and handle and they have excellent antiseizure qualities. Their excellent corrosion-resistant properties make these alloys especially well-suited for bearing applications in compressors, electric motors, and food-processing equipment.

Lead-Base Alloys

Lead-base bearing materials (lead babbitts) are alloys of lead, tin, antimony, and in many cases arsenic. Many such alloys have been used for centuries as type metals and were probably first employed as bearing materials because of the properties they were known to possess. The advantage of arsenic additions have been generally recognized since 1938. Table 4 lists nominal compositions of the most widely used lead babbitts according to ASTM, SAE, and ISO specifications. Mechanical properties of some of these alloys are given in Table 5.

Table 4 Designations and nominal composition of lead-base bearing alloys

Designation				Composition, %					Product form	Applications
UNS	**SAE**	**ISO**	**ASTM (B 23)**	**Pb**	**Sb**	**Sn**	**As**	**Other**		
L53346	Alloy 13	PbSb10Sn6	Alloy 13	84	10	6	. . .	. . .	Cast on steel or steel-backed bronze	Bimetal and trimetal surface layer
L53585	Alloy 14	PbSb15Sn10	Alloy 7	75	15	10	. . .	. . .	Cast on steel back	Bimetal surface layer
L53620	Alloy 15	PbSb15SnAs	Alloy 15	84	15	1	1	. . .	Cast on steel back	Bimetal surface layer
. . .	. . .	PbSb14Sn9CuAs	. . .	77	14	9	0.5	1 Cu	Cast on steel back	Bimetal surface layer
L53565	. . .	. . .	Alloy 8	80	15	5	0.5	. . .	Cast on steel back	Bimetal surface layer
. . .	. . .	. . .	(a)	87.5	9	3.5	. . .	. . .	Cast on bronze back	Bimetal surface layer

(a) ASTM B 67

Table 5 Typical mechanical properties of chill cast lead-base bearing alloys

Designation				Compressive yield strength[a]				Ultimate tensile strength, 20 °C (68 °F)		Elongation, 20 °C (68 °F),%	Hardness, HB	
				20 °C (68 °F)		**100 °C (212 °F)**					**20 °C (68 °F)**	**100 °C (212 °F)**
UNS	**SAE**	**ISO**	**ASTM (B 23)**	**MPa**	**ksi**	**MPa**	**ksi**	**MPa**	**ksi**			
L53346	Alloy 13	PbSb10Sn6	Alloy 13	22.8	3.30	10.7	1.55	69	10.0	5	19	8.5
L53585	Alloy 14	PbSb15Sn10	Alloy 7	24.5	3.55	11.0	1.60	72	10.5	4	22.5	10.5
L53620	Alloy 15	PbSb15SnAs	Alloy 15	24.8	3.60	14.5	2.10	71	10.4	2	21	13
L53565	. . .	. . .	Alloy 8	23.4	3.40	11.0	1.60	69	10.0	5	20	9.5

(a) 0.125% offset

For many years, lead-base bearing alloys were considered to be only low-cost substitutes for tin alloys. However, the two groups of alloys do not differ greatly in antiseizure characteristics, and when lead-base alloys are used with steel backs and in thicknesses <0.75 mm (<0.03 in.), they have fatigue resistance that is equal to, if not better than, that of tin alloys. Bearings of any of these alloys remain serviceable longest when they are ≤0.13 mm (≤0.005 in.) thick (see Fig. 1).

In the absence of arsenic, the microstructures of these alloys comprise cuboid primary crystals of SbSn or of antimony embedded in a ternary mixture of Pb-Sb-SbSn in which lead forms the matrix. The number of these cuboids per unit volume of alloy increases as antinomy content increases. If antimony content is >15%, the total amount of the hard constituents increases to such an extent that the alloys become too brittle to be useful as bearing materials.

Arsenic is added to lead babbitts to improve their mechanical properties, particularly at elevated temperatures. All lead babbitts are subject to softening or loss of strength during prolonged exposure to the temperatures (95 to 150 °C, or 200 to 300 °F) at which they serve as bearings in internal combustion engines. Addition of arsenic minimizes such softening. Under suitable casting conditions, the arsenical lead babbitts--for example, SAE 15 (ASTM grade 15)--develop remarkably fine and uniform structures. They also have better fatigue strength than arsenic-free alloys.

Pouring temperature and rate of cooling markedly influence the microstructures and properties of lead alloys, particularly when they are used in the form of heavy liners for railway journals. High pouring temperatures and low cooling rates, which typically result from the use of overly hot mandrels, promote segregation and formation of a coarse structure. A coarse structure may cause brittleness, low compressive strength, and low hardness. Therefore, low pouring temperatures (325 to 345 °C, or 620 to 650 °F) usually are recommended. Because these alloys remain relatively fluid almost to the point of complete solidification (~240 °C, or 465 °F, for most compositions), they are easy to manipulate and can be handled with no great loss of metal from drossing.

Lead-Base Electroplated Overlays. The improvement in fatigue life that can be achieved by decreasing babbitt layer thickness has already been noted. Economically as well as mechanically, it is difficult to consistently achieve very thin uniform babbitt layers bonded to bimetal shells by casting techniques. Therefore, the process of electroplating a thin precision babbitt layer on a very accurately machined bimetal shell was perfected. Specially designed plating racks allow the thickness of the plated babbitt layer to be regulated so accurately that further machining is usually not required.

Electroplated tin alloys were found to be generally inferior to lead alloys, and only lead alloys are in commercial use as electroplated bearing overlays. SAE alloy 192 (88Pb10Sn2Cu) is the most frequently used. Tin in alloys 191 (90Pb10Sn), 192 and 193 (80Pb18Sn2Cu) and indium in alloy 194 (93Pb7In) imparts corrosion resistance. Tin also increases wear resistance. Both copper and indium enhance fatigue resistance. Plated overlays generally range in thickness from 0.013 to 0.05 mm (0.0005 to 0.002 in.), with fatigue life increasing markedly as overlay thickness decreases.

Copper-Base Alloys

Copper-base bearing alloys comprise a large family of materials with a wide range of properties. They include commercial bronze, copper-lead alloys, and leaded and unleaded tin bronzes. They are used alone in single-metal bearings, as bearing backs with babbitt surface layers, as bimetal layers bonded to steel backs, and as intermediate layers in steel-backed trimetal bearings.

The moderate strength and hardness of pure copper are readily increased by alloying, most commonly with tin (with which copper forms a solid solution). Lead is present in cast copper-base bearing alloys as a nearly pure, discrete phase, because its solid solubility in the matrix is practically nil. The lead phase, which is exposed on the running surface of a bearing, constitutes a site vulnerable to corrosive attack under certain operating conditions.

The antifriction behavior of copper-base bearing alloys improves as lead content increases, although at the same time strength is degraded because of increased interruption of the continuity of the copper alloy matrix by the soft weak lead. Thus, through judicious control of tin content, lead content, and microstructure, a large family of bearing alloys has evolved to suit a wide variety of bearing applications.

Table 6 gives specification numbers and nominal compositions of copper-base bearing alloys, as well as the forms in which the alloys are used and general notations on typical product applications. Table 7 shows the ranges of mechanical strength properties that are exhibited by copper-base bearing alloys.

Table 6 Designations and nominal composition of copper-base bearing alloys

No.	Designation				Composition, %				Product form	Applications
	UNS	**SAE**	**ISO**	**Other**	**Cu**	**Sn**	**Pb**	**Zn**		
Commercial bronze										
1	C83420	Alloy 795	. . .	. . .	90	0.5	. . .	9.5	Wrought strip	Solid bronze bushings and washers
Unleaded tin bronzes										
2	C52100	. . .	CnSn8P	. . .	92(a)	8	. . .	. . .	Wrought strip	Solid bronze bushings and washers
3	C90300	. . .	. . .	. . .	88	8	. . .	4	Cast tubes	Solid bronze bearings
4	C90500	. . .	. . .	. . .	88	10	. . .	2	Cast tubes	Solid bronze bearings
5	C91100	. . .	. . .	. . .	84	16	. . .	. . .	Cast tubes	Solid bronze bearings
6	C91300	. . .	. . .	. . .	81	19	. . .	. . .	Cast tubes	Solid bronze bearings
Low-lead tin bronzes										
7	C92200	. . .	. . .	. . .	88.5	6	1.5	4	Cast tubes	Solid bronze bearings
8	C92300	. . .	. . .	. . .	87	8.5	0.5	4	Cast tubes	Solid bronze bearings
9	C92700	. . .	. . .	. . .	87.5	10	2	0.5	Cast tubes	Solid bronze bearings
Medium-lead tin bronzes										
10	C83520	Alloy 791	. . .	. . .	88	4	4	4	Wrought strip	Solid bronze bushings and washers
11	. . .	. . .	. . .	F32/F62	88	4	4	4	Cast on steel back	Bimetal bushings and washers, trimetal intermediate layer
12	C83600	. . .	CuPb5Sn5Zn5	. . .	85	5	5	5	Cast tubes	Solid bronze bearings, bronze bearing backs
13	C93200	. . .	CuSn7Pb7Zn3	. . .	83	7	7	3	Cast tubes	Solid bronze bearings
14	. . .	Alloy 793	. . .	. . .	88	4	8	. . .	Cast on steel back	Bimetal surface layer
15	. . .	Alloy 793	. . .	. . .	88	4	8	. . .	Sintered on steel back	Bimetal surface layer
16	C93700	. . .	CuPb10Sn10	. . .	80	10	10	. . .	Cast tubes	Solid bronze bearings, bronze bearing backs
17	. . .	Alloy 792	CuPb10Sn10(G)	. . .	80	10	10	. . .	Cast on steel back	Bimetal surface layer, trimetal intermediate layer
18	. . .	Alloy 792	CuPb10Sn10(P)	. . .	80	10	10	. . .	Sintered on steel back	Bimetal surface layer
High-lead tin bronzes										
19	C93800	. . .	. . .	. . .	78	7	15	. . .	Cast tubes	Solid bronze bearings, bronze bearing backs
20	. . .	. . .	. . .	AMS 4825	74	10	16	. . .	Cast on steel back	Bimetal surface layer

21	. . .	Alloy 794	CuPb24Sn4(G)	. . .	73.5	3.5	23	. . .	Cast on steel back	Bimetal surface layer, trimetal intermediate layer
22	. . .	Alloy 794	CuPb24Sn4(P)	. . .	73.5	3.5	23	. . .	Sintered on steel back	Bimetal surface layer, trimetal intermediate layer
23	. . .	. . .	. . .	F112	72.5	2.5	25	. . .	Cast on steel back	Trimetal intermediate layer
24	C94300	. . .	. . .	. . .	70	5	25	. . .	Cast tubes	Solid bronze bearings
Copper-lead alloys										
25	. . .	Alloy 49	CuPb24Sn(G)	. . .	75	1	24	. . .	Cast on steel back	Trimetal intermediate layer
26	. . .	Alloy 49	CuPb24Sn(P)	. . .	75	1	24	. . .	Sintered on steel back	Trimetal intermediate layer
27	. . .	Alloy 48	CuPb30(P)	. . .	70	. . .	30	. . .	Sintered on steel back	Bimetal surface layer, trimetal intermediate layer
28	. . .	Alloy 485	. . .	. . .	48	1	51	. . .	Sintered on steel back, infiltrated with lead	Bimetal surface layer

(a) Also 0.3 P

Table 7 Typical room-temperature mechanical properties of copper-base bearing alloys

Alloy family	Product form	Compressive yield strength[(a)]		Ultimate tensile strength		Hardness, HB
		MPa	**ksi**	**MPa**	**ksi**	
Commercial bronze	Wrought strip	. . .	. . .	310-440	45-64	78-115
Unleaded tin bronzes	Wrought strip	. . .	. . .	400-580	58-84	80-160
	Cast tubes	90-125	13-18	240-310	35-45	70-170
Low-lead tin bronzes	Cast tubes	. . .	. . .	275-290	40-42	65-77
Medium-lead tin bronzes	Wrought strip	. . .	. . .	310-440	45-64	78-115
	Cast tubes	90-100	13-14	240-255	35-37	60-65
	Steel backed	. . .	. . .	. . .	. . .	50-130
High-lead tin bronzes	Cast tubes	75-85	11-12	185-210	27-30	48-55
	Steel backed	. . .	. . .	. . .	. . .	55-90

(a) 0.1% offset

Commercial Bronze. Lead-free copper alloys are characterized by poor antifriction properties but fairly good load-carrying ability. Wrought commercial bronze strip (SAE 795) with 10% Zn can be readily press formed into cylindrical bushings and thrust washers. Strength can be increased by cold working this inexpensive material.

Unleaded Tin Bronze. The unleaded copper-tin alloys are known as phosphor bronzes because they are deoxidized with phosphorus. They are used principally in cast form as shapes for specific applications, or as rods or tubes from which solid bearings are machined. They have excellent strength and wear resistance, both of which improve with increasing tin content, but poor surface properties. They are used for bridge turntables and trunnions in contact with high-strength steel and in other slow-moving applications.

Low-Lead Tin Bronzes. The inherently poor machinability of tin bronzes can be improved by adding small amounts of lead. Such additions do not significantly improve surface properties, however, and applications for these alloys are essentially the same as those for unleaded tin bronzes.

Medium-Lead Tin Bronzes. The only wrought strip material in this group of alloys is SAE 791, which is press formed into solid bushings and thrust washers. C83600 is used in cast form as bearing backs in bimetal bearings. SAE 793 is a low-tin, medium-lead alloy that is cast or sintered on a steel back and used as a surface layer for medium-load bimetal bushings. SAE 792 is higher in tin and slightly higher in lead; it is cast or sintered on a steel back and used for heavy-duty applications such as wrist pin bushings and heavy-duty thrust surfaces.

High-Lead Tin Bronzes. These contain medium-to-high amounts of tin and relatively high lead contents to markedly improve antifriction characteristics. SAE 794, widely used in bushings for rotating loads, has the same bronze matrix composition as SAE 793 (4.5% Sn) but three times as much free lead. It is cast or sintered on a steel back and used for somewhat higher speeds and lower loads than alloy 793. The bronze matrix of SAE 794 is much stronger than that of a plain 75-25 copper-lead alloy. Alloy 794 can be used as the intermediate layer with a plated overlay in heavy-duty trimetal bearing applications such as main and connecting-rod bearings in diesel truck engines. This construction provides the highest load-carrying ability available in copper alloy trimetal bearings.

Copper-Lead Alloys. These are used extensively in automotive, aircraft, and general engineering applications. These alloys are cast or sintered to a steel backing strip from which parts are blanked and formed into full-round or half-round shapes depending on final application. Copper-lead alloys continuously cast on steel strip typically consist of copper dendrites perpendicular and securely anchored to the steel back, with an interdendritic lead phase. In contrast, sintered copper-lead alloys of similar composition are composed of more equiaxed copper grains with intergranular lead phase.

High-lead alloy SAE 48 can be used bare on steel or cast iron journals. Tin content in this alloy is restricted to a minimum value to maintain a soft copper matrix, which together with the high lead content improves the antifriction/antiseizure properties of the alloy. Bare bimetal copper-lead bearings are used infrequently today because the lead phase, present as nearly pure lead, is susceptible to attack by corrosive products that can form in the crankcase lubricant during extended oil-change periods. Therefore, most copper-base alloys with lead contents >20%, including both SAE alloy 48 and alloy 49, are now used with plated overlays in trimetal bearings for automotive and diesel engines.

SAE 485 is a special sintered and infiltrated composite material. By these methods, it is possible to combine a very strong continuous copper alloy matrix structure with a very high lead content and to alloy the lead-rich constituent with sufficient tin to make it resistant to corrosion. SAE 485 is used principally for bushing and bearing applications that involve alignment, shaft surface finish, or unusual dirt contamination problems.

Aluminum-Base Alloys

Successful commercial use of aluminum alloys in plain bearings dates back to about 1940, when low-tin aluminum alloy castings were introduced to replace solid bronze bearings for heavy machinery. Production of steel-backed strip materials by roll bonding became commercially successful about 1950, permitting the development of practical bimetal and trimetal bearing material systems using aluminum alloys in place of babbitts and copper alloys.

The ready availability of aluminum and its relatively stable cost have provided an incentive for continuing development of its use in plain bearings. Aluminum single-metal, bimetal, and trimetal systems can now be used in the same load ranges as babbitts, copper-lead alloys, and high-lead tin bronzes. Moreover, the outstanding corrosion resistance of aluminum has become an increasingly important consideration in recent years and has led to widespread use of aluminum alloy materials (in the place of copper-lead alloys and leaded bronzes) in automotive engine bearings.

Designations and Compositions. Alloy designations and nominal compositions of aluminum-base alloys in most extensive commercial use are listed in Table 8. In these alloys, additions of silicon, copper, nickel, magnesium, and zinc function to strengthen the aluminum through solid-solution and precipitation mechanisms. Fatigue resistance and the opposing properties of conformability and embeddability are largely controlled by these elements and by the use of appropriate heat treatments. Tin and lead are instrumental in upgrading the inherently poor compatibility of aluminum. Cadmium is also used as an alloy addition for this reason. Silicon has a beneficial effect on compatibility in addition to its moderate strengthening effect. Although not well understood theoretically, this compatibility-enhancing mechanism is of considerable practical value. Silicon is used effectively in many alloys for this reason (usually in conjunction with tin, lead, or cadmium).

Table 8 Designations and nominal composition of aluminum-base bearing alloys

No.	Designation				Composition, %							Product form	Applications
	UNS	**SAE**	**ISO**	**Other**	**Al**	**Si**	**Cu**	**Ni**	**Mg**	**Sn**	**Other**		
High-tin alloys													
1	A08081	Alloy 783	AlSn20Cu	. . .	79	. . .	1	. . .	. . .	20	. . .	Wrought strip, bonded to steel back	Bimetal surface layer
2	. . .	Alloy 786	. . .	. . .	59.5	. . .	0.5	. . .	. . .	40	. . .	Wrought strip, bonded to steel back	Bimetal surface layer
High-lead alloys													
3	. . .	Alloy	. . .	F-85	85	4	1	. . .	. . .	1.5	8.5 Pb	Powder roller	Bimetal surface

		787										strip, bonded to steel back	layer
4	. . .	Alloy 787	. . .	Al-6	88.5	4	0.5	. . .	. . .	1	6 Pb	Wrought strip, bonded to steel back	Bimetal surface layer
Intermediate-tin alloys													
5	. . .	Alloy 788	. . .	SA-151	82.5	3	1	. . .	. . .	12	1.5 Pb	Wrought strip, bonded to steel back	Bimetal surface layer
6	. . .	Alloy 788	. . .	AS-124	82	4	2	. . .	. . .	12	. . .	Wrought strip, bonded to steel back	Bimetal surface layer
7	. . .	Alloy 788	. . .	A-17-X	83	2.5	0.7	. . .	. . .	12	2 Pb, 0.2Sb	Wrought strip, bonded to steel back	Bimetal surface layer
8	. . .	Alloy 788	. . .	FA-130	81	3	0.7	. . .	. . .	13	2 Pb, 0.2 Sb, 0.2 Sr	Wrought strip, bonded to steel back	Bimetal surface layer
Low-tin alloys													
9	. . .	. . .	AlSn6CuNi	. . .	91.5	. . .	1	1	. . .	6.5	. . .	Cast tubes	Solid aluminum alloy bearings
10	A08500	. . .	. . .	. . .	90.5	. . .	1	1	1	6.5	. . .	Cast tubes	Solid aluminum alloy bearings
11	A08510	. . .	. . .	. . .	89.5	2.5	1	0.5	. . .	6.5	. . .	Cast tubes	Solid aluminum alloy bearings
12	A08520	. . .	. . .	. . .	89.5	. . .	2	1.2	1	6.5	. . .	Cast tubes	Solid aluminum alloy bearings
13	A08280	Alloy 780	. . .	. . .	90.5	1.5	1	0.5	. . .	6.5	. . .	Wrought strip and plate	Solid aluminum alloy bearings
14	. . .	Alloy 770	AlSn6CuNi	. . .	91.5	. . .	1	1	. . .	6.5	. . .	Wrought strip, bonded to steel back	Bimetal surface layer, trimetal intermediate layer
15	A08280	Alloy 780	. . .	. . .	90.5	1.5	1	0.5	. . .	6.5	. . .	Wrought strip, bonded to steel back	Bimetal surface layer, trimetal intermediate layer
Tin-free alloys													
16	A04002	Alloy 781	AlSi4Cd	. . .	95	4	0.1	. . .	0.1	. . .	1 Cd	Wrought strip, bonded to steel back	Bimetal surface layer, trimetal intermediate layer
17	A04002	Alloy 781	AlSi4Cd	F-154	95	4	0.1	. . .	0.1	. . .	1 Cd	Wrought strip, bonded to steel back, precipitation hardened	Trimetal intermediate layer
18	. . .	Alloy 782	AlCd3CuNi	. . .	95	. . .	1	1	. . .	. . .	3 Cd	Wrought strip, bonded to steel back	Bimetal surface layer, trimetal intermediate layer
19	. . .	Alloy 784	AlSi11Cu	. . .	88	11	1	. . .	. . .	. . .	. . .	Wrought strip, bonded to steel back	Trimetal intermediate layer
20	. . .	Alloy 785	AlZn5Si2CuPb	. . .	91.5	1.5	1	. . .	. . .	. . .	5 Zn, 1 Pb	Wrought strip, bonded to steel back	Trimetal intermediate layer

Mechanical properties are of more value in predicting the fabrication behavior of aluminum-base bearing alloys than in predicting their bearing performance. With the exception of solid aluminum alloy bearings, in which there is no steel back and where press-fit retention depends entirely on the strength of the aluminum alloy, mechanical properties of finished bearings are rarely specified, usually for control purposes only. Consideration of some of these properties (Table 9) does, however, contribute to an understanding of these alloys as a family of related engineering materials and of their relationship to the better-known structural aluminum alloys in addition to the copper-base, tin-base, and lead-base bearing alloys discussed previously.

Table 9 Typical room-temperature mechanical properties of aluminum-base bearing alloys

Alloy family	Product form	Compressive yield strength[a]		Ultimate tensile strength		Hardness, HB
		MPa	**ksi**	**MPa**	**ksi**	
High-tin alloys	Steel backed	. . .	. . .	100-130	15-19	25-40
High-lead alloys	Steel backed	. . .	. . .	. . .	. . .	40-50
Intermediate-tin alloys	Steel backed	. . .	. . .	. . .	. . .	50-60
Low-tin alloys	Cast tubes	70-140	10-20	125-220	18-32	45-65
	Wrought plate	80-140	12-120	140-170	20-25	40-55
	Steel backed	. . .	. . .	. . .	. . .	35-45
Tin-free alloys	Steel backed	. . .	. . .	. . .	. . .	35-65

(a) 0.2% offset

Product Applications. The majority of the current commercial applications of aluminum-base bearing alloys involve steel-backed bimetal or steel-backed trimetal bearings. To determine the most cost-effective aluminum material for any specific application, consideration should be given to the economic advantages of bimetal versus trimetal systems. The higher cost of the high-tin and high-lead alloys usually is offset by eliminating the cost of the lead alloy overlay plate. If the higher load capacity of a trimetal material is required, it then becomes important to select an aluminum liner alloy that provides adequate but not excessive strength, so that conformability and embeddability are not sacrificed unnecessarily. The tin-free alloy group (alloys 16 to 20 in Table 8) offers a wide range of strength properties, and the most economical choice usually is found in this group.

Other Bearing Materials

The zinc-base alloys that have been used successfully for machinery bearings are standard zinc foundry alloys of the Zn-Al-Cu-Mg, high-performance type (alloys ZA-12 and ZA-27). Tubular shapes made by conventional sand, permanent mold, and pressure die-casting methods are machined into bearings in the same way that solid bronze bearings are made. Most applications have been direct substitutions for solid bronze bearings; the substitutions are made primarily to reduce costs. Maximum recommended running temperatures for zinc-base bearing alloys range from 95 to 120 °C (205 to 250 °F), which is approximately 100 °C (180 °F) below the temperature limits for copper-base and aluminum-base bearing alloys.

Silver-Base Alloys. Use of silver in bearings is largely confined to unalloyed silver (AMS 4815) electroplated on steel shells, which then are machined to very close dimensional tolerances and finally precision plated to size with a thin overlay of soft metal. The overlay can be lead-tin, lead-tin-copper, lead-indium, or in some cases, pure lead. As a bearing material, plated silver is invariably used with an overlay. Silver on steel with an overlay is regarded as the ultimate fatigue-resistant bearing material.

Gray cast irons are standard materials for certain applications involving friction and wear (for example, brake drums, piston rings, cylinder liners, and gears). Cast irons perform well in such applications and thus should be given consideration as bearing materials.

Cemented Carbides. Extremely hard materials, including cemented tungsten carbides, titanium carbides, and other combinations have been used successfully for various specialized bearing and seal applications. In terms of the bearing performance characteristics listed in Table 1, these materials exhibit essentially zero conformability and embeddability, but rank high in strength, hardness, corrosion resistance, and compatibility.

Nonmetallic bearing materials are widely used for a variety of applications. They have many inherent advantages over metals, including better corrosion resistance, lighter weight, better resistance to mechanical shock, and the ability to function with very marginal lubrication or with no lubricant present at all. The major disadvantages of most nonmetallics are their high coefficients of thermal expansion and their low thermal conductivity characteristics. For many years, carbon-graphites, wood, rubber, and laminated phenolics dominated the field of nonmetallic bearing materials. In the early 1940s, development of nylon and polytetrafluoroethylene (PTFE, or Teflon) gave engineering designers two new nonmetallics with very unique characteristics, particularly the ability to operate dry.

A wide variety of polymer composites is now being used very successfully in bearing applications. The addition of fiber reinforcements and fillers such as solid lubricants and metal powders to the resin matrix can significantly improve the physical, thermal, and tribological properties of these plastics.

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Biomaterials

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Introduction

BIOMATERIALS are the man-made metallic, ceramic, and polymeric materials used for intracorporeal applications in the human body. Intracorporeal uses may be for hard tissue or soft tissue replacement. Metallic materials are the primary focus in this section; limited information is provided on ceramics, polymers, composites, cements, and adhesives, especially where they interact with metallic materials.

Metals frequently are used in the body for orthopedic purposes--such as hip stems and balls, knees, and so on--where hard tissue (bony structures) must be repaired or replaced. Metals also find application as stents (in angioplasty), leads and cases (in pacemakers), and surgical clips or staples. Dental applications of metals center around amalgam or gold to repair cavities or replace broken teeth, titanium alloys for posts on which to fix crowns or bridges, and nickel-chromium alloys and cobalt-chromium alloys for crowns and bridgework, partial dentures, or as the basis for porcelain-coated alloy teeth. Stainless steel and a few other alloys find use as wires and sheet in orthodontics.

Ceramics are used as the ball in the articulating region of a hip joint, as bioactive coatings on implants, and in certain aspects of dental use--for example, as fillers or for porcelain enameling (a ceramic process). Carbon finds use in heart valves and dental implants. As for polymeric materials, silicone has been used in joint replacement, polymethyl methacrylate (PMMA) as a cement (grout), and ultrahigh molecular-weight polyethylene (UHMWPE) as the acetabular cup in hip joints. Composite materials, particularly polymeric material composites, are used in dental applications, but their use is limited elsewhere in the body. Composites or ceramics intended to resorb in the body have been shown to have potential application. Resorbable materials in the body are not new; resorbable sutures have been in use for many years.

Body Conditions. Temperature conditions are not extreme for the materials used, body temperatures being a little less than 38 °C (100 °F). However, the chemical physiological environment and biomechanical environment can be extreme. For structural implants used to repair the hip, it is estimated that the average nonactive person may place 1 to 2.5×10^6 cycles of stress on his or her hip in a year. For a person 20 to 30 years of age, with a life expectancy of 70 to 80 years, that is the equivalent of approximately 10^8 cycles of loading in a lifetime. The actual loads and cycles are a function of the weight and activity level of the person, but the need for longtime cyclic capability in fatigue is obvious. Other applications in the body also impart many millions of fatigue cycles to the device or component implanted.

In considering the parameters of materials for intracorporeal applications, several factors are of major importance. It is generally agreed that the material must:

- Be nontoxic and noncarcinogenic, cause little or no foreign body reaction, and be chemically stable and corrosion resistant. This is known as biocompatibility.
- Be able to endure large and variable stresses in the highly corrosive environment of the human body
- Be able to be fabricated into intricate shapes and sizes

Many structural applications of materials in the body require that the replacement material fit into a space perhaps only one-fourth the area of the part being permanently or temporarily replaced or assisted. Consequently, the implant may have to withstand loads up to 16 or more times that which the human bone must withstand. In restorative dentistry, high compressive biting forces are combined with large temperature changes and acidity to produce a challenging environment. It is clear that there can be very great mechanical loading demands on biomaterials used for structural purposes.

The chemical structure of the body can cause corrosive attack, which may degrade the implant and/or cause release of ions that may adversely affect the body. This chemical interaction is described in terms of the biocompatibility of the biomaterial. Biocompatibility must consider the release of ions or molecules, the mobility of released species, and the interaction of released species or material surfaces with the body. Some ions or molecules are severely detrimental to the body. Among other things, a material might be carcinogenic, be thrombogenic (cause clotting), cause cell mutations, produce a fever, or cause sensitization. Ions released could cause tissue necrosis. The essence of developing a biomaterial has been to find a material with the necessary mechanical and/or physical properties that cause no damage, or a limited amount, to the human body.

Mechanical Behavior. Metals generally are required to have both high static and cycle-dependent properties. Tensile yield and ultimate strength, modulus of elasticity, and fatigue endurance limit are the principal metallic strength attributes that must be determined. Temperature is not an issue. For dental materials, which experience very high point forces in the mouth, creep and compressive yield strengths are important. Ceramics offer excellent compressive yield, and thus are often used for such applications. Tension and bending or tension fatigue are not primary strength attributes for study in ceramics because tensile loads cause relatively rapid nonductile crack propagation.

Important mechanical properties of polymeric materials include tensile strength, creep strength, modulus, and fatigue strength. Creep can be important because the operating temperature of the body is a significant fraction of the melting or glass transition temperature for polymers. The first polymeric material (Teflon) used for an acetabular cup failed because of extreme distortion due to creep.

Wear resistance is also an important criterion for all biomaterials. Excessive wear can lead to premature mechanical failure of the replacement component. More importantly, wear debris may not be biocompatible with the body.

Under ideal conditions, mechanical property tests would be made in environments identical to that in the human body (i.e., in vivo). Practically, mechanical property tests are run either in normal air environments or, where the degrading effects of environment must be evaluated, in simulated human physiological solutions.

Corrosion. Metals used as biomaterials must be either noble or corrosion resistant to the body environment. Many types of corrosion have been observed on biomaterials used in the body, including general corrosion, pitting and crevice corrosion, stress-corrosion cracking, corrosion fatigue, and intergranular corrosion. None of these forms, with the exception of general corrosion, can be tolerated in surgical implant materials. For a material to be considered resistant to corrosion in the body, its general corrosion rate usually must be less than 0.01 mil/year (0.00025 mm/year). For comprehensive discussions of corrosion testing procedures and results, see the articles "Corrosion of Metallic Implants and Prosthetic Devices" and "Tarnish and Corrosion of Dental Alloys" in *Corrosion,* Volume 13 of the *ASM Handbook.*

Corrosion testing of ceramic materials is not common practice because the corrosion of oxide ceramics used for structural implants is very low. However, ceramics do show degradation of properties in vivo. Polycrystalline ceramics of the alumina type show loss in static strength when exposed to body fluids. This strength loss is a form of environmental degradation. Generally, the greater the purity and the greater the density (lesser porosity) of a ceramic, the more resistant it is to strength loss in the body. Bioactive ceramics represent a different aspect of corrosion because they are expected to transform into bony structures by gradually releasing their cations and anions to be incorporated in the growing bone or tissue structure. Corrosion testing is not implicitly required for bioactive ceramics.

Polymeric materials are not necessarily subjected to what is normally defined as corrosion; nevertheless, they do break down in the body. The result can be tissue interaction with residual monomers remaining after polymerization, chemical degradation of molecular structure of the polymer, and leaching of additives such as plasticizers, fillers, and colorants. Some polymers are designed to degrade (resorb) in the body; others degrade but are not intentionally designed to do so. The deterioration of polymers can affect the main polymer chain, cross links, and side groups. Sometimes, undesirable cross linking can occur and degrade a linear polymer, while in other cases a desired cross link is broken by interaction of thermal energy or other elements (e.g., oxygen) with the polymer. Some polymers absorb lipids or interact with proteins; hydrolysis occasionally can occur.

The body environment is quite hostile to man-made materials, and polymers will start to degrade as soon as they are implanted. Hydroxyl (OH^-) ion attack or interactions with dissolved oxygen are the principal chemical sources of polymer degradation. The degradation of polymers in the body is much more complex than the attack of metals and ceramics.

Regulatory Issues. Biomaterials cannot be separated from the regulatory processes that govern their use. It can take years to gain approval for new materials if they are substantially different from any used and approved previously. Because the approval process can be costly, biomaterials development and application tend to follow existing tracks or at least claim to be doing so when regulatory approval is requested.

Metallic Biomaterials for Implants

Metals have been successfully used as biomaterials for many years. Figures 1, 2, and 3 show typical implant applications for orthopedic purposes. Figure 4 shows intramedullary rods and illustrates their use for fracture fixation. There are numerous other structural metallic implants.

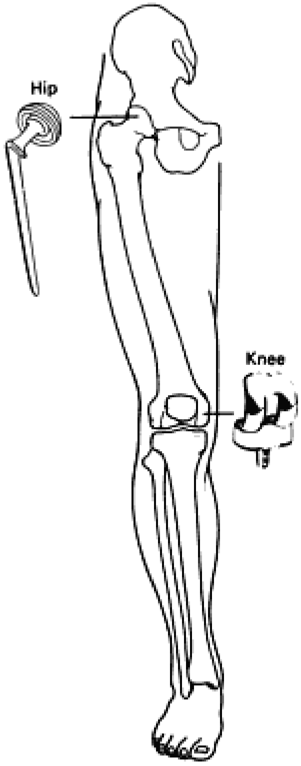

Fig. 1 Diagram of total hip and knee replacements showing component shape and location of implantation

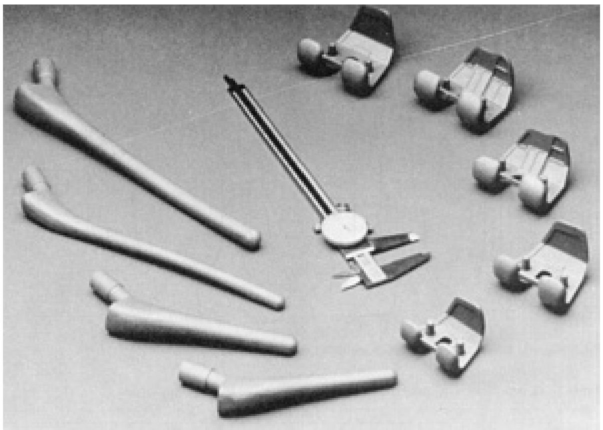

Fig. 2 Investment cast titanium alloy knee and hip implant prostheses

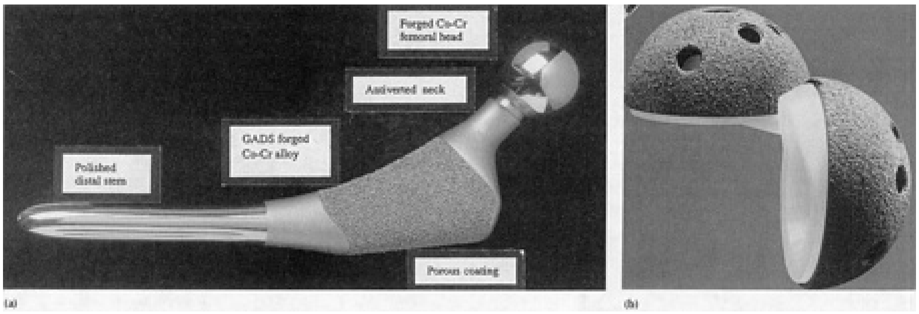
Forged Co-Cr femoral head
Antiverted neck
GADS forged Co-Cr alloy
Polished distal stem
Porous coating
(a)
(b)

Fig. 3 Total hip replacement implant. (a) Femoral components. GADS, gas-atomized dispersion-strengthened alloy. (b) Acetabular cup components, which are fitted over the femoral head, featuring plasma sprayed shell with anatomic screw hole placement. Courtesy of Howmedica Inc., Pfizer Hospital Products Group

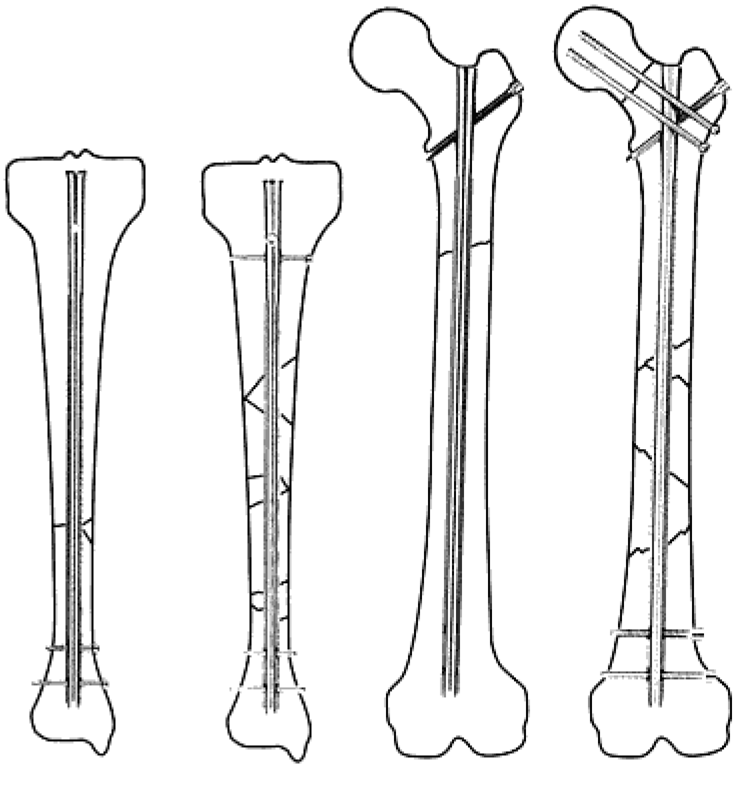

Fig. 4 Intramedullary rods and locking nails applied to tibia or femur

Hip arthroplasty generally requires that the upper femur (thigh bone) be replaced and the mating pelvis (hip bone) area replaced or resurfaced. Femoral components usually are manufactured from cobalt-chromium or titanium alloys. The ball (articulating portion of the femoral component) is made either of highly polished cobalt-chromium alloys or of ceramic. Modular designs where the stem and ball are of two different materials are common. Similarly, the polymeric socket of the common acetabulum replacement can be implanted directly in the pelvis or be part of a modular arrangement wherein the cup is placed into a metal shell. Design variations include the modular approach, straight stems, curved stems, platforms and no platforms, holes and no holes in the femoral stem, and so on.

Relatively few metals in industrial use are biocompatible and capable of long-term success as an implant in the body. For structural applications in the body, the principal metals are AISI 316L stainless steel, cobalt-chromium alloys originating from modifications of the alloy Vitallium (Haynes Stellite Alloy No. 21), and Ti-6Al-4V. There are limited uses for gold. Tantalum finds use as cranial plates or surgical staples (along with stainless steel), as do four grades of commercial-purity titanium. Table 1 lists the compositions of alloys used as implantable biomaterials; Table 2 indicates relative strengths for these alloys. The overall chemistry and properties of metallic materials generally are covered by ASTM specifications. Table 3 lists selected ASTM specifications dealing with implantable biomaterials.

Table 1 Compositions of some metals and alloys used as surgical implants

Metal or alloy	Composition(a), %							
	C	**Ti**	**Cr**	**Fe**	**Co**	**Ni**	**Mo**	**Others**
AISI type 316 stainless steel	0.08 max	. . .	18.5	bal	. . .	12.0	3.0	0.75 Si, 0.03 P, 0.03 S
Cast cobalt-chromium alloy	0.36 max	. . .	28.5	0.75 max	bal	2.5 max	6.0	1.0 max Si
Wrought cobalt-chromium alloy	0.15 max	. . .	20.0	3.0 max	bal	2.5 max	. . .	15.3 W
Unalloyed titanium	0.10	bal	. . .	0.30	. . .	. . .	. . .	0.015 H, 0.13 O, 0.07 N
Ti-6Al-4V	0.08	bal	. . .	0.25	. . .	. . .	. . .	6.0 Al, 4.0 V, 0.0125 H, 0.13 O
MP35N	. . .	. . .	20.0	. . .	35.0	35.0	10.0	. . .
Unalloyed tantalum	0.01	0.01	. . .	0.01	. . .	. . .	0.01	bal Ta, 0.001 H, 0.015 O, 0.01 N, 0.005 Si, 0.03 W, 0.05 Nb

(a) Nominal unless otherwise indicated

Table 2 Mechanical properties of some metals and alloys used as surgical implants

Metal or alloy	Yield strength		Tensile strength		Elongation, %	Modulus of elasticity (*E*)	
	MPa	**ksi**	**MPa**	**ksi**		**GPa**	**10^6 psi**
316 stainless steel, annealed	207	30	517	75	40	. . .	. . .
316 stainless steel, cold worked	689	100	862	125	12	200	29
Cast cobalt-chromium alloy	450	65	655	95	8	248	36
Wrought cobalt-chromium alloy	379	55	896	130	. . .	242	35
Titanium, grade 4	485	70	550	80	15	110	16
Ti-6Al-4V, annealed	830	120	895	130	10	124	18
Ti-6Al-4V, heat treated	(a)	(a)	(a)	(a)	. . .	. . .	. . .
Tantalum, annealed	140	20	205	30	. . .	. . .	. . .
Tantalum, cold worked	345	50	480	70	. . .	. . .	. . .
MP35N, annealed	240-655	35-95	795-1000	115-145	. . .	228	33

(a) Subject to agreement between purchaser and manufacturer

Table 3 Selected ASTM specifications dealing with biomaterials

ASTM No.	Biomaterial

F 55, F 138	Low-carbon stainless steels (type 316L)
F 75, F 90	Cobalt-chromium alloys
F 67	Commercially pure titanium
F 136	Ti-6Al-4V
F 451	Acrylic bone cement
F 560	Unalloyed tantalum
F 603	High-purity dense aluminum oxide
F 648	Ultra-high molecular-weight polyethylene (UHMWPE)
F 881	Silicone gel and solid silicone

Fatigue and yield strengths vary not only by alloy type (e.g., stainless steel versus titanium) but also with processing. The modulus, however, is more or less set by the alloy type. The lowest moduli (110 to 125 GPa, or 16 to 18 × 10^6 psi) are for titanium alloys, while stainless steels have moduli near 205 GPa (30 × 10^6 psi), and cobalt-chromium alloys have moduli even higher, approximately 240 GPa (35 × 10^6 psi). The modulus is an important concern in the orthopedic application of biomaterials. Bone has a modulus on the order of 17 GPa (2.5 × 10^6 psi). The discrepancy between the modulus of bone and that of the alloys used to support structural loads means that the metallic devices implanted in the body take a disproportionate share of the load (stress). Bone adapts to applied stress (Wolff's Law). Because alloys cause stress shielding one result of the adaptation is that the bone associated with the implant does not become or remain as strong as it would in the absence of an implant. The ideal alloy would have the modulus of magnesium, the strength of cobalt-chromium alloys, the corrosion resistance and biocompatibility of titanium, and the fabricability of stainless steel.

Alloys used in articulating prosthesis applications are often used in conjunction with other biomaterials such as UHMWPE, polyoxymethylene (Delrin-150), or aluminum oxide ceramics. A typical hip prosthesis consists of the stem, a ball, and a socket with a metallic backing.

The chemistry and manufacturing processes for metallic biomaterials are not necessarily unique to the biomedical device industry. Control of undesired elements is an important aspect of the successful application of metallic biomaterials. The principal requirement for each alloy is that it be corrosion resistant when inserted in the body and that it have optimum mechanical properties. For a discussion of the physical metallurgy of stainless steel, cobalt-chromium, and titanium alloys, consult the appropriate Sections in this Handbook.

One of the unique aspects of the biomaterials and biomedical device industry is that, despite the general adherence to the ASTM or other standards, materials are marketed and discussed in trade names. Thus, an alloy that has chemical origins which can be traced to a common cobalt-chromium alloy might have the following names: Vitallium, Alivium, Endocast, Orthochrome, Protasul, and Zimaloy. It is necessary for each trade-marketed alloy to be reviewed to determine its underlying composition--that is, to which ASTM or other specification it is being made and sold.

Stainless steels and cobalt-chromium alloys depend for their general corrosion resistance on the presence of chromium and its ability to render the alloys passive. Additions of other alloy elements enhance resistance to nonuniform types of corrosion (e.g., pitting). Titanium and titanium alloys develop passivity without chromium. Surface passivity is the most important criteria, but surface finish also can affect performance. Highly polished surfaces perform better in terms of corrosion and wear.

Stainless steels are popular because they are relatively inexpensive, they can be formed with common techniques, and their mechanical properties can be controlled over a wide range for optimum strength and ductility. Stainless steels are used as wrought alloys. Passivity of stainless steel implants is enhanced by nitric acid passivation before the implant is sterilized and packaged for delivery to a medical facility.

Stainless steels are not sufficiently corrosion resistant for long-term use as an implant material. They find use as bone screws, bone plates, intramedullary rods, and other temporary fixation devices with a number of applicable ASTM specifications. For example, ASTM F 55 describes stainless steel that contains 17 to 19% Cr, 12 to 14% Ni, 2 to 3% Mo, a maximum of 0.03% C, and maximum limits on several other elements. AISI 316L, which is covered by ASTM F 55 and F 138, is the most commonly used stainless biomaterial because it resists pitting corrosion better than other stainless alloys. Despite its improved resistance to pitting, type 316L can be susceptible to crevice corrosion, as are most stainless steels.

The stainless steels used for implants are austenitic, which accounts for their good formability. Vacuum melting improves the fatigue capabilities of the alloys (AISI 316LVM, which is ASTM F 138). Cold working increases strength and fatigue resistance. Type 316L stainless steel can be welded, but care must be taken not to sensitize the component. Types 302, 304, 304VAR (vacuum arc remelted), and 316L have been used as wire for limited-duration applications in the body. Welding and soldering are used to join one wire section to another or to form smooth tips on guide wires.

As noted, the corrosion resistance of stainless steel is not sufficient for long-term use in the body; plates, screws, and other components implanted during reconstructive surgery are invariably removed after bones have knit and sufficient bone strength has been achieved. Early hips implanted in the 1960s used stainless steel, but cobalt-chromium or titanium alloys are now the metallic materials of choice for long-term implants.

Cobalt-chromium alloys were first used in the 1930s. The alloy Vitallium was used as a cast dental alloy and then adapted to orthopedic applications starting in the 1940s. The corrosion resistance of cobalt-chromium-base alloys is more than an order of magnitude greater than that of stainless steels, and they possess high mechanical property capability.

These alloys were first used as cast components. Later, wrought cobalt-chromium alloys came into use. Although a number of ASTM specifications exist for cobalt-chromium-base biomaterials, the two main alloys used are Co-28Cr-6Mo (ASTM F 75), a casting alloy, and Co-20Cr-10Ni (ASTM F 90), a wrought alloy. Wrought processing has been applied to modified compositions that fall under F 75.

The metallurgy for cobalt-chromium alloys is the same as that for cobalt-base superalloys. Strengthening is produced by solid-solution elements and the presence of carbides. In wrought alloys where working is possible, cold work enhances strength. In order to produce wrought cobalt-chromium alloys, carbon must be reduced compared to the level in cast alloys (0.05% versus about 0.25% or higher). Low carbon contents mean that less strengthening is produced by carbides. To enhance fabricability, chromium contents generally are reduced and nickel added. Wrought alloys can be hot worked and some can be cold drawn. Yield strengths vary with grain size and the degree of cold work imparted from the wrought fabrication process.

Alloys produced for structural applications such as hip prostheses can be forged if optimum properties are desired. The forging process results in maximum strength and toughness for cobalt-chromium alloys but may not produce uniform grain sizes. Data have been reported on forging of a modified F 75 composition wherein finer grain size occurred in the distal end (tip of the femoral stem, farthest from the ball) than in the proximal end. Strength (fatigue, yield) was correspondingly better in specimens taken from the distal end.

Cobalt-chromium alloys are difficult to machine. Closed-die forging can minimize machining requirements, but wrought processed components still may require more machining than cast components. Consequently, investment casting often is used to produce cobalt-chromium implants at the lowest cost. The grain size of cast components is invariably greater than that of comparable wrought components, so strength properties of castings do not approach those of wrought cobalt-chromium alloys. Porosity can be a problem in castings but can be controlled by improved mold design and by application of hot isostatic pressing (HIP) in postcast treatment of vacuum investment cast alloys. Powder metallurgy has been used to make some cobalt-chromium components. Hot isostatic pressing of powder is claimed to result in very fine grains and exceptional properties, but costs may be higher.

The preferred method of producing cobalt-chromium alloy implants will be a function of the trade-off between cost and properties. Where the properties of castings are sufficient, castings will dominate. When maximum strength is required, hot pressing and/or forging will rule. Table 2 shows that forged cobalt-chromium alloys have substantial mechanical property advantages over the cast alloy. Because of the significant differences in chemistry between the cast and wrought compositions, concern may arise that the strengths of wrought alloys are a function of chemistry. Table 4 compares the strengths of virtually identical cobalt-chromium alloys (low carbon and slightly lower chromium in wrought) tested in the cast and forged conditions. The strength advantage of forging is obvious.

Table 4 Effect of forging on Vitallium alloy mechanical properties

Material condition	Tensile strength		0.2% yield strength		Elongation, %	Fatigue strength (10^6 cycles implied, *R* = -1)	
	MPa	**ksi**	**MPa**	**ksi**		**MPa**	**ksi**
Forged							
Proximal stem	1406.6	204.0	889.5	129.0	28.3	792.9	115.0
Distal stem	1506.6	218.5	1029.4	149.3	27.5	827.4-965.3	120.0-140.0
Cast (typical)	790	115	520	75	15	310	45

Titanium and its alloys used for implant devices have been designed to have excellent biocompatibility, with little or no reaction with tissue surrounding the implant. Titanium derives its corrosion resistance from the stable oxide film that forms on its surface, which can reform at body temperatures and in physiological fluids if damaged. Although many titanium alloys have been developed, primarily for industrial application, Ti-6Al-4V alloy and the four grades of commercially pure titanium have found the most use in the body. Other titanium alloys such as Ti-6Al-17Nb and Ti-15Mo also have biomaterials applications.

The mechanical properties of commercial-purity titanium are a function of oxygen level. Increasing oxygen levels increase yield strength and decrease ductility. Ti-6Al-4V has much greater yield and ultimate strengths than the pure metal, as well as good ductility (Table 2), and offers one of the best combination of properties among all structural implant metals. The alloy generally is produced by forging but can be cast; it can be strengthened by controlling the composition and by adjusting the manufacturing process. Titanium alloys undergo a transition in crystal structure on heating. The transition temperature (to the high-temperature, body-centered cubic phase, β) is called the βtransus. Processing in various methods in the vicinity of the βtransus can refine the microstructure. By appropriate processing, it is possible to increase fatigue life by a factor of two or more.

The friction and wear properties of titanium are quite different from those of most other metals. This is a result of its tenacious oxide film. The film will remain intact under low loads and slow sliding speeds in articulating conditions. However, if the film is worn away and not regenerated promptly, galling will cause metal-to-metal contact and cold welding. This process leads to very high friction and wear rates; consequently, titanium-to-titanium (or to other metal) articulating joints are not used. Methods such as ion beam implantation and nitriding can be useful for improving wear.

The wear properties of titanium probably prevent its more widespread use in orthopedic prostheses. For the most part, however, titanium is not articulated against other metallic materials or itself, but is used for components of modular construction where a titanium femoral stem will be used with a cobalt-chromium or a ceramic ball to articulate against a UHMWPE liner (e.g., in a total hip replacement).

Shape memory effect (SME) alloys are able to "remember" a prior shape even if the component undergoes significant deformation. The shape memory alloy component will stay in its deformed shape until the material is heated to a transition temperature, at which point the component will spontaneously return to its original shape.

One class of SME alloys is represented by nickel-titanium alloys of roughly equiatomic composition. It was reasoned that nickel-titanium alloys should be reasonably biocompatible and corrosion resistant and could be used for temporary fracture fixation. Applications of nickel-titanium alloys include osteosynthesis plates, jaw plates, and dental braces.

To illustrate the application of SME alloys, consider osteosynthesis plates. These are attached to a bone to stabilize a fracture and promote healing. The plate is produced in its desired final geometry using a SME alloy, then is stretched 8% and cooled. Screw attachment holes are drilled without heating the plate. Then the plate is attached to the patient's fractured bone. A local heat source (warm water or hot air) is applied to raise the temperature to above the transition temperature; the plate reverts to its original dimensions, contracting and pulling the fractured surfaces together.

Coatings for Use on Implants

One of the great debates in orthopedic implant surgery has been over the question of attachment of bone to prosthetic devices. The principal reason for revision operations on implants (especially now that corrosion problems have been largely overcome by removing stainless steels from articulating prostheses) has been loosening of the prosthesis. Improved bonding of the prosthesis to the bone should enhance the stability of a prosthesis and reduce the chances for loosening. Various procedures have been developed in an attempt to increase the bond strength of joints. Some of these procedures tried to promote bony ingrowth into the implant using porous coatings, with varying degrees of success.

One procedure consisted of attaching, to the implant surface, fibers of an alloy compatible with the basis alloy to produce a porous metal coating. Titanium fibers were used on Ti-6Al-4V implants. An alternate procedure was to attach metal powder particles (often spherical). Powder metallurgy techniques were used to put Co-Cr-Mo on a Co-Cr alloy implant, and commercial-purity titanium powders were plasma sprayed on Ti-6Al-4V implants. Results from these trials have been mixed, but many implants are available with a porous metallic surface coating on part of the implant surface. In addition to concern about the efficacy of the attachment process, for titanium alloys (which are subject to notch-induced fatigue failure) it was felt that reduced fatigue life might arise due to the notches produced by powders on the surface.

The most effective processes for promoting improved attachment have used calcium phosphate ceramics (calcium hydroxyapatite, HA), which provide elements found in bone. The concept involves bonding a thin layer of a biologically active calcium HA coating to the implant. The coating must be capable of being resorbed by the body, which then substitutes natural bone for the calcium phosphate. A high-strength bond is maintained with the metallic implant by avoiding the fibrous tissue layer often encountered between implant and bone.

Hydroxyapatite coatings have been applied by the plasma spray process. Because the bond between an HA coating and the substrate is a mechanical one, the implant surface must be roughened; the degree of roughness influences interfacial strength. Variations in coating composition and stability affect clinical success. Hydroxyapatite coatings are considered useful in producing enhanced bond strengths, but results vary.

Metallic Biomaterials for Dentistry

Dental amalgam has been in use since the 1800s, generally with limited known detrimental effects on humans. Dental amalgam is made by mixing mercury and a powdered alloy containing silver, tin, copper, and zinc. The amalgam has a composition close to the Ag_3Sn γ phase. The amalgamation reaction produces a solidified alloy over a short time range, allowing the dentist to manipulate the pasty amalgam in the tooth cavity. Dental amalgam is used to restore chewing surfaces and is subject to heavy forces. The aim of the amalgam is to develop an acceptable compressive strength in the restoration within several hours without compromising the manipulative ability of the amalgam. The dimensional stability of the amalgam during setup is important for its clinical application. Longtime phase changes can occur in amalgam, which may affect performance. Table 5 lists the properties of some alloys used in dentistry.

Table 5 Properties of some typical dental alloys

	Proportional limit		Yield strength, 0.1% offset		Modulus of elasticity		Strain, %	Ultimate tensile strength(b)		Brinell hardness, kg/mm^2
	MPa	**ksi**	**MPa**	**ksi**	**GPa**	**10^6 psi**		**MPa**	**ksi**	
Amalgam										
New True Dentalloy	. . .	. . .	. . .	. . .	21.3	3.1	. . .	54 [318]	7.9 [46.1]	. . .
Dispersalloy	. . .	. . .	. . .	. . .	33.8	4.9	. . .	48 [423]	6.9 [61.3]	. . .
Conventional gold-alloys										
Type I, Ney Oro A	69	10	. . .	. . .	. . .	. . .	29.5	221	32	45
Type II, Ney Oro A-1	190	27.5	. . .	. . .	. . .	. . .	32	379	55	95
Type III, Ney Oro B-2										
Soft	221	32.0	. . .	. . .	. . .	. . .	35	421	61	110
Hard	262	38.0	. . .	. . .	. . .	. . .	34	448	65	120
Type IV, Ney Oro G-3										
Soft	286	41.5	. . .	. . .	99.3	14.4	24	469	68	140
Hard	572	83.0	. . .	. . .	. . .	. . .	6.5	758	110	220
Low-gold-alloys										
40 Au-Ag-Cu (Forticast)										
Soft	. . .	. . .	379	55.0	. . .	. . .	18	562	81.5	177
Hard	. . .	. . .	738	107	. . .	. . .	2	889	129	252
10 Au-Ag-Pd (Paliney)										
Soft	438	63.5	. . .	. . .	. . .	. . .	17	558	81.0	150
Hard	583	84.5	. . .	. . .	. . .	. . .	7	731	106	205
Ag-Pd (Albacast)										
Soft	. . .	. . .	262	38.0	. . .	. . .	10	434	63	130
Hard	. . .	. . .	324	47.0	. . .	. . .	8	469	68	140
Porcelain fused to metal gold alloy										
Ceramco O	. . .	. . .	. . .	. . .	86.2	12.5	5	. . .	. . .	131
Nickel-chromium alloy										
Crown and bridge alloys	. . .	. . .	359	52	179.3	26.0	1.1	421	61	330 HV
Partial denture alloys	. . .	. . .	710	103	. . .	. . .	2.4	807	117	. . .
Porcelain fused to metal alloys	. . .	. . .	. . .	. . .	202.7	29.4	16	917	133	270 HV
Cobalt-chromium alloy										
Cast Vitallium	. . .	. . .	644	93.4	217.9	31.6	1.5	869	126	. . .

Wires										
Austenitic stainless steels	. . .	. . .	1372	199(a)	200.6	29.1	. . .	. . .	. . .	. . .
Elgiloy	. . .	. . .	1110	161(a)	171.0	24.8	. . .	. . .	. . .	. . .
β-titanium	. . .	. . .	586	85(a)	71.7	10.4	. . .	. . .	. . .	. . .
Nitinol	. . .	. . .	193	28(a)	42.1	6.1	. . .	. . .	. . .	. . .
Tooth structure										
Enamel	353	51.2	. . .	. . .	. . .	. . .	. . .	10 [384]	1.5 [55.7]	343 HV
Dentin	167	24.2	. . .	. . .	. . .	. . .	. . .	52 [297]	7.5 [43.1]	68 HV

(a) 0.05% offset.

(b) Bracketed values are ultimate compressive strengths

When a tooth cavity is restored by using an amalgam, there is no adhesion between the amalgam and the tooth material. This can cause marginal leakage of the restoration (filling). The dimensional stability of the amalgam during setup and its ability to reproduce the convolutions of the cavity walls, along with the technique of the dentist in mixing and applying the amalgam, affect leakage. Deterioration of fillings can occur by localized or crevice corrosion in crevices, pores, and cracks or at margins.

Dental amalgam is brittle, which can lead to failure in tension or creep. Dentists avoid this by feathering edges and minimizing chances for high tensile loads. Dental amalgam creeps under load; the mercury content of the amalgam affects creep resistance.

Amalgam chemistry has changed over the years. Production of improved spherical powder shapes enhanced setup of the amalgam restoration. In addition, copper was introduced to modify the phase reaction by eliminating the so-called γ_2 phase, which is the tin-mercury phase responsible for most long-term corrosion of fillings.

Gold alloys are typically used for crowns and bridgework, although persons concerned about the health aspects of mercury in silver-tin amalgams have opted for gold cavity restorations. In this latter instance, the malleability of gold is used to good advantage. Thin foils of pure gold are produced and mechanically deformed into the tooth cavity to produce a filling.

Pure gold is used in wrought form for fillings or as a cast material for bridges and crowns. In some circumstances gold also is used for dental wires and in alloyed form as a dental solder. Because gold is not particularly strong, alloys have been developed to improve strength for castings. Gold foil, although soft when applied, hardens due to the cold work it receives during insertion into the cavity. The hardness of a properly compacted gold foil filling is about twice that of cast gold. Gold fillings are claimed to so closely adapt to the contours of the cavity that no marginal leakage occurs.

Gold alloys used for castings fall into four categories according to hardness and strength. Type I alloys use solid-solution additions. The type II to IV alloys contain varying elements to produce hardening reactions by solution hardening and by heat treatment. As the alloy type number increases, the percentage of gold in the alloy decreases, so that type IV alloys are relatively low in tarnish resistance. Commercial dental alloys usually range in gold content from approximately 50 to 88%.

Other Metallics. Cast cobalt-chromium alloys are used in dentistry for fixed bridges and for partial dentures as the framework for attachment of teeth (Fig. 5), as are nickel-chromium alloys. Austenitic stainless steels are used for partial dentures and, occasionally, as mesh frameworks to strengthen full dentures. Wrought cobalt-chromium, nickel-chromium, and stainless steel are available as wires for orthodontic use. All these alloys are less dense than gold alloys. In the case of cobalt-chromium alloys, improved mechanical properties (compared to gold), coupled with decreased density, permit the manufacture of lighter and thinner dental prostheses.

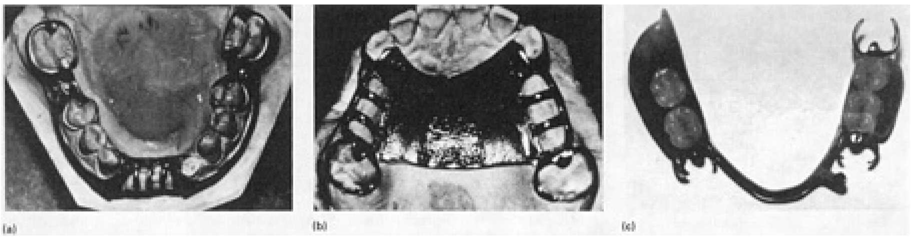

Fig. 5 Removable partial dentures showing cobalt-chromium alloy uppers and lowers (a and b) plus completed partial denture set with teeth attached (c)

Titanium alloys seem uniquely suited for dental implant applications, particularly as single or multiple posts on which to attach a few teeth (Fig. 6) or a permanent denture. Use of implants inserted into the mandible (lower jaw) or maxilla (upper jaw) provides an anatomically satisfactory way to transfer the stresses of chewing to the bone. Threaded and smooth implants have been used with success, although threaded implants seem to be superior. Titanium dental implants have remarkably good integration with the bony structure of the jaw.

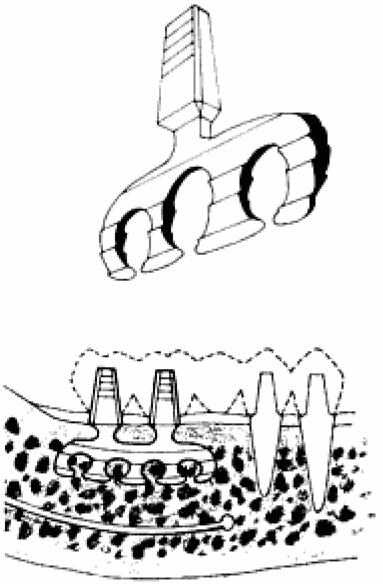

Fig. 6 Illustration of uncoated dental implant and its use. The posts function as a support for replacement teeth.

Extractive Metallurgy

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Introduction

THE REVERSION of metals into compounds is a natural phenomenon also known as corrosion or oxidation. Over time, a piece of steel will turn into rust; this process of reversion is natural because it results in the metal lowering its free energy. Thus, spontaneous or natural reversion is associated with a release of energy. The more active or reactive the metal, the higher its tendency to return to its natural state.

The science of preventing metals from undergoing this natural process is known as corrosion protection or oxidation protection. Because a metal desires to be in a stable compound form, its natural state must therefore be an oxidized form, such as an oxide, sulfide, carbonate, sulfate, chloride, or nitrate. This natural state is called an ore or a mineral. The process of dissociating these compounds and converting them into a metal (and a nonmetal) is known as extraction. The dissociation of the compound into metals and nonmetals is called reduction.

Naturally, the process of extraction requires that energy be spent in order to force the metal to disengage from its compound. When the form of this energy is primarily thermal, the process is known as pyrometallurgy. Processes that use electrical or chemical energy to perform the reduction are known as electrometallurgy and hydrometallurgy, respectively.

The extractive metallurgy applied to the production of a particular metal may involve one or more of these distinct metallurgical processes. Although hydrometallurgy implies processing through an aqueous medium, it may involve heat for enhanced kinetics and/or favorable thermodynamics. The size and concentration of ore suitable for each of these processes differ widely. Electrometallurgy usually is not used directly on the ore concentrate in the scheme of metal extraction. Generally, a purer metal compound feed is required for metal extraction through electrometallurgy, whereas hydrometallurgical and pyrometallurgical techniques are suitable for treating a beneficiated ore. This Section will discuss the basic principles of these major types of metallurgical processes in further detail, and will show the path of metal extraction from an ore to the finished metal.

Until recently, the field of extractive metallurgy was concerned mainly with producing metals from their oxidized/combined state or natural ore, which is known as primary metal production. However, like everything else, metals have a limited life. Once a metal becomes part of an engineered system--as an alloy, intermetallic, or surface-modified product--its usefulness depends on the continued usefulness of the entire system, which is generally cut short at some point, often by corrosion. In the present industrial environment, valuable metals cannot be discarded. Regeneration or recycling of metals back into a useful form, which is known as secondary metal production, often requires the same extractive metallurgy principles and sophisticated separation methods as does the reduction of ore. The entire field of waste minimization, remediation, recovery, and recycling is fast becoming an integral part of extractive metallurgy.

The development of radically new methods for extraction of metals is rare. In recent times, research and development efforts in extractive metallurgy have focused on managing existing processes more efficiently. Small improvements in processing methods have yielded large gains in productivity and profitability. New recycling methods also are under development, since recycled metal and extracted metal have different properties. The aluminum, zinc, lead, copper, and precious metals industries have made great strides in secondary production over the last two decades. All of this technology development now takes into account environmental concerns, such as air and water pollution and health hazards.

Mining of Minerals and Ores

More than 98 wt% of the earth's crust comprises eight elements: oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium. These elements are not distributed uniformly, but occur as concentrated ore deposits of one mineral form or the other. These ore deposits form by (1) magmatic segregation, (2) solution and precipitation, and (3) physical phenomena, such as erosion and concentration. Geophysical, geochemical, and extraterrestrial methods are available for locating a useful mineral deposit and estimating its commercial worth.

An ore can be defined as "a naturally occurring aggregate of minerals from which a metal or metals may be extracted at a profit." Several factors are considered in the decision to exploit a mineral deposit: extent of the deposit, required mining method, grade or rank of the deposit, available facilities for mining, cost of mining with respect to metal price, metal demand forecast, ore processing and extraction costs, and the socioeconomic as well as environmental impact of the mining activity. This decision is also time sensitive, being strongly influenced by changing technological, economic, and social constraints.

The ore minerals that are most simple to treat are those where the valuable metal occurs in its elemental or native form; in such cases physical separation or liberation is sufficient for metal production. However, chemical and thermal means are often necessary to liberate the metal due to its low concentration. Not many metals occur naturally as elements; the chief examples are gold, silver, and platinum. Other metals have been found in elemental form, but not to the extent needed for economic exploitation. The metals found in their elemental form are usually noble metals, since they are inherently non-reactive or inert. Most metals occur in the earth's crust combined with other nonmetallic elements in the form of minerals. There are relatively few minerals of economic importance. Also, a particular mineral deposit may be used to extract several metals as they are often found together, such as copper, gold, lead, zinc, antimony, bismuth, molybdenum, and arsenic.

Most common minerals of high tonnage metals (iron, aluminum, copper, titanium, nickel, chromium, magnesium, zinc, and others) are either an oxide or a sulfide deposit. Several of the oxides or sulfides are present together in a chemically combined form in the deposit. While the oxide or sulfide of a particular metal (usually the highest weight percent) is the primary component being extracted, it must be separated from the others. These other oxides or sulfides comprise the gangue of the ore. The composition and nature of the gangue material accompanying the valuable mineral is of great concern. The type of process required for extraction depends largely on the nature of the gangue in terms of its basicity or acidity. The amount and composition of gangue dictates the type of flux required for preparing a proper slag to enable the metal extraction.

Thus, an ore can be relatively simple or exceedingly complex, but in essence will consist of: (a) the primary valuable mineral, (b) the predominant gangue content, (c) valuable by-products, and (d) detrimental impurities. The composition of the valuable mineral dictates to some extent the type of metallurgical reduction process used. The composition of the gangue will also influence the reduction processes that can be used. Valuable by-products may increase the economic return from a given ore, such as the occurrence of gold in copper ores, the presence of silver in lead ores, and the recovery of molybdenum from copper ores. Finally, the presence of certain impurities may increase the cost of treatment or even make processing unfeasible; examples are arsenic in copper ores and bismuth in lead ores. For further information on the mining methods and common ore and mineral types for metal extraction, see Ref 1 and 2.

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Mineral Processing

Mineral processing refers to a group of physical and chemical steps that make the ore amenable for metal extraction by creating a concentrate of the metal compound of interest. *Mineral beneficiation* and *ore dressing* are terms used interchangeably for mineral processing. Mineral processing steps also allow the valuable by-products to preferably segregate with the concentrate while rejecting some of the predominant gangue. It should be realized that mineral processing, in certain cases, can provide two or more separate streams, each forming a source of value. The chemical changes affected to the ore are no more than superficial. Physical separation processes are based on the exploitation of the gravimetric, magnetic, and electrostatic properties of various ore fractions. This is often enhanced by sizing, sieving, and washing. The most commonly used flotation processes utilize the differences in surface properties that can be altered by surface chemistry. Mineral processing separates some of the gangue in natural ores by operations that do not change the mineralogical status of the valuable metal. As a result mineral processing increases the percentage of the valuable mineral by lowering the gangue content. The rejected material is referred to as tailings or tails.

Mineral processing is economically justified by the early removal of partial gangue so that a smaller volume of concentrate has to be shipped for extraction rather than the bulky low-grade ore. In the majority of installations, the mineral processing facilities--such as crushers, grinders, concentrators, separators, and flotation devices--are near the mine, while the reduction plant may be in a more central location some distance away. It is desirable to ship concentrates to the reduction plant where other ancillary equipment and facilities required for down-line processing are readily available. Direct-smelting ores existed in the past when the upper portions of veins were being mined and the ore was rich and relatively low in gangue. Such resources are now rare.

Crushing, Grinding, and Classification

The chunky crude ore must first be broken down in size to release the valuable mineral from its physical bonds with the gangue. The extent of the subdivision of the ore to obtain a reasonable degree of liberation depends on the characteristics of the individual ore. Ores are referred to as fine grain or coarse grain to describe the average natural particle size of the valuable mineral constituents as well as that of the gangue. Ore samples are crushed and ground to varying extents and the product is separated into size fractions by sieving on set of laboratory screens with elutriation of the subsieve fraction. The size fractions are examined under the microscope to determine the extent of liberation, and concentration tests are run on size fractions to determine the degree of concentration that can be obtained. The extent of comminution to obtain the higher degree of concentration through greater liberation must be justified by the increased cost of grinding. When the particle size is very small, concentration processes do not work as efficiently and tailing losses are high. In addition, fine ore is unsuitable for several pyrometal-lurgical processes, such as the blast furnace smelting. Particle size reduction is achieved by two- or three-stage procedures referred to as crushing and grinding; the combination of the two is known as comminution. Three basic types of crushing and grinding circuits are shown in Fig. 1.

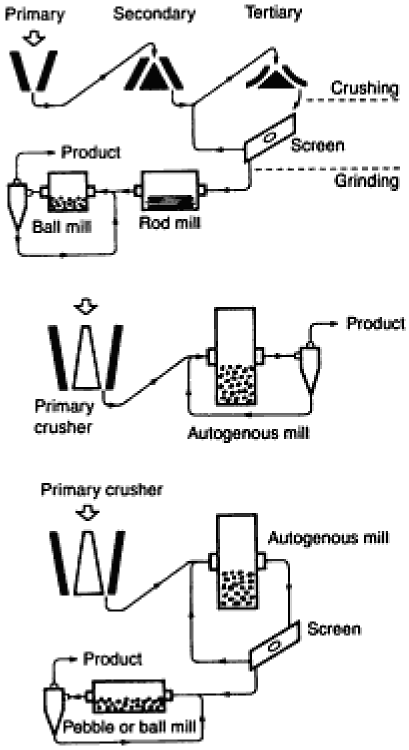

Fig. 1 Three basic types of crushing-and-grinding circuits. (a) Conventional. (b) Autogenous. (c) Autogenous with separate fine grinding

Crushing reduces ore pieces 1 to 2 ft in diameter or larger to pieces averaging 100 to 150 mm (4 to 6 in.) in diameter. Schuhmann has shown a linear relationship between successive screen sizes and the logarithm of cumulative percent retained on each size of screen (Ref 3). Many devices have been proposed for coarse crushing, but jaw or gyratory crushers are mostly used for the normal ores. Sometimes short-head cone crushers are used for intermediate reduction of the size of the gyratory- or jaw-crusher product (Ref 4).

Grinding follows coarse crushing, and possibly intermediate crushing, to take the ore from a maximum size of a few inches to smaller sizes needed for reasonable liberation. Of the many devices and procedures invented for grinding, most plants use a tumbling grinding mill in which the grinding media are steel or ceramic balls, steel rods, or pieces of the ore itself. This latter process is called "autogenous" grinding. The grinding operation can be conducted either wet or dry, but normally in ore mills wet grinding is used because the subsequent concentration process is also wet. Avoidance of severe dust problems and the merits of wet classification lot particle-size control are other advantages of wet grinding.

A mill can be operated in the open-circuit mode, where the ore is added at the feed end and the entire product is accepted at the discharge end. In this case, the reduction in particle size for all of the ore is essentially completed in one pass that produces considerable overgrinding of most of the feed. An alternative scheme is to put the grinding mill in the closed-circuit mode with a classifying device. The mill is operated so that not all of the ore is sufficiently reduced in size, but the mill discharge is fed to a classifier which returns the oversize particles to the mill feed and permits the undersize particles to continue on to the next step in the process.

Classification is defined as separation of particles according to their settling rates in a fluid, normally water, although dry classifiers are commonly used for collecting dust from crushing operations. Wet classifiers used in conjunction with grinding can be subdivided into mechanical and hydraulic classifiers. A spiral (mechanical) classifier, to which pulp from a grinding mill is fed, forces the larger and heavier particles to settle to the bottom of the pool which are then conveyed by the spiral for more grinding. The smaller and lighter particles overflow and are ready for the next step in the process. In a hydraulic classifier (hydrocyclone), the fine particles in the overflow are discharged from the top, and the coarse particles in an underflow are discharged at the bottom.

Concentration Devices

Gravity Devices. Minerals are usually higher in density than the gangue, and therefore, various devices can be used for separation. The classical miner's pan and rocking cradle have been replaced by more sophisticated shaking tables or a jig that can be mechanized to handle larger quantities of material and to achieve better separation. However, these installations are unable to treat the fine particles generated by the extent of grinding necessitated by fine ore-gangue textures.

Magnetic Devices. Separation based on magnetic properties is widely used for concentration of iron ores. If the iron mineral is magnetite, the magnetite particles can be attracted by permanent magnets or electromagnets to separate them from the gangue, as shown in Fig. 2. If the iron ore is predominantly hematite (Fe_2O_3), a partial reduction can convert the hematite to the magnetic magnetite (Fe_3O_4), making magnetic separararation feasible. For a successful magnetic separation it is imperative that the mineralogy of the magnetic and nonmagnetic fractions of the ore are distinct and separable.

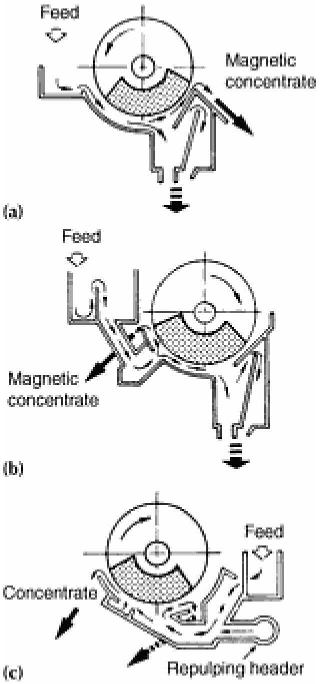

Fig. 2 Wet-drum low-intensity magnetic separator tanks. (a) Concurrent. (b) Counter-rotation. (c) Counter-

current. (Courtesy of Eriez Magnetics)

Electrostatic Devices. The separation on the basis of differences in electrostatic properties requires the ore be in a limited size range like sand. The ore is fed onto a conducting and grounded rotor and is exposed to an ionizing electrode. The particles pick up a charge and then those that are conducting lose the charge to the rotor and are thrown off. The nonconducting particles retain their charge, cling to the rotor, and are brushed off into a separate container. This procedure has been successful in the treatment of beach sands. In conjunction with magnetic and gravity separation, electrostatic devices can separate rutile, ilmenite, chromite, garnet, magnetite and silica fractions.

Flotation is the most widely used method for concentrating nonferrous ores, particularly sulfides. It can also be applied to oxidized forms of minerals with limited efficiency. The separation is based on whether or not mineral surfaces are wettable. The finely ground ore in an aqueous pulp is fed to a flotation machine with an impeller that provides vigorous agitation. Air is introduced into the cell either from a compressed-air line or by the pumping action of the impeller. The air bubbles, distributed by the agitation, rise through the pulp and attach to the nonwetted mineral particles, carrying them to the surface where a froth is formed that can be scraped from the cell. The wetted particles, usually the gangue, do not attach to the bubbles, and hence remain in the pulp to be discharged as tailings. A single one-pass separation is usually not sufficient, and the rougher concentrate may be recleaned. Likewise, the tailings from the first separation may be scavenged to avoid discarding valuable minerals. The retreatment, regrinding, and other elaborate steps lead to a complex flow sheet. These flow sheets have been optimized by mathematical modeling, and sensitive instrumentation has resulted in greater efficiency and a high degree of control.

Only graphite and molybdenite have nonwettable surfaces necessary for particles to adhere to bubbles and be carried to the surface. Usually, reagents must be added to the pulp to change the surface properties. Oils were used at one time to give sulfides an oily surface that would make them float without affecting the gangue remaining in the pulp. Today, selective reagents, which can distinguish among various sulfides, are used. These reagents, called *collectors,* are added along with other agents that will stabilize the froth, depress or activate selected minerals, control pH, and generally improve the collection and selection of desired minerals.

Disposal of Tailings

The concentrate products from any of the wet concentrating processes require dewatering. The initial step is thickening in a large cylindrical tank. The stream of concentrate and water enters the tank where the mineral particles settle to the bottom, and slowly revolving rakes move the mud-like deposit to a center discharge. The overflow, practically devoid of solids, can be returned to the process if dissolved reagents are not detrimental. The thickened underflow pumped from the concentrate thickeners is normally sent to a vacuum filter of a drum or disk type, which reduces the moisture content of the cake to about 10% or less.

The tailings from the mill may be further thickened if there is a need to recover more of the mill water. Otherwise, the tailings are discharged through pipes or flumes to the tailing pond where the remaining particles settle out over a period of time allowing the top clear water to be discarded.

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Flow Diagrams of Extraction Processes

As mentioned earlier, the final combination of unit processes to form the complete flow sheet for the extraction of any metal from its ore depends on the type and cost of raw materials, cost of processing, and the demand for the metal. The cost of energy is a major factor in the cost of processing; as higher purity metal is required, more energy is required to produce it. However, the unit processes are essentially classified as pyro-, hydro-, or electrometallurgical. Figures 3, 4, and 5 show flow diagrams for copper, iron, and zinc (Ref 5), which clearly indicate a combination of these three types of basic metallurgical unit steps. For example, the two alternative routes for zinc production are either completely pyrometallurgical (Fig. 5, left) or a combination of all three (Fig. 5, right). The flow sheet for copper (Fig. 3) shows a combination of pyro metallurgical and electrometallurgical steps. The iron extraction flow sheet (Fig. 4) is essentially a combination of pyrometallurgical unit processes. The purity of the metal product also depends on the chosen route. Electrolytic refining as the final step in extraction yields a product of higher purity. Pyrometallurgical processes generally yield a product with impurities unless the product is further refined. For complete description of thermodynamic and kinetic characteristics of these unit processes, see Ref 6, 7, and 8.

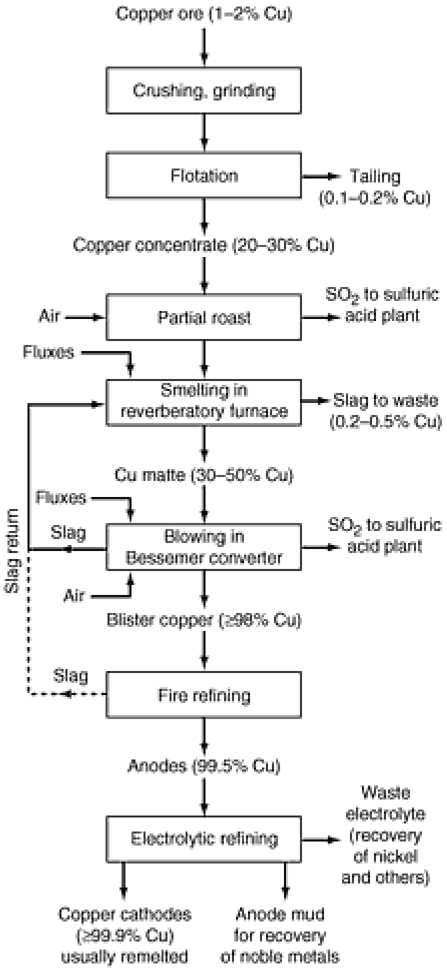
Copper ore (1–2% Cu)
Crushing, grinding
Flotation
Tailing (0.1–0.2% Cu)
Copper concentrate (20–30% Cu)
Air
Partial roast
SO2 to sulfuric acid plant
Fluxes
Smelting in reverberatory furnace
Slag to waste (0.2–0.5% Cu)
Cu matte (30–50% Cu)
Fluxes
Slag
Blowing in Bessemer converter
SO2 to sulfuric acid plant
Air
Slag return
Blister copper (≥98% Cu)
Slag
Fire refining
Anodes (99.5% Cu)
Electrolytic refining
Waste electrolyte (recovery of nickel and others)
Copper cathodes (≥99.9% Cu) usually remelted
Anode mud for recovery of noble metals

Fig. 3 Typical flow sheet for the production of copper from copper sulfide ore

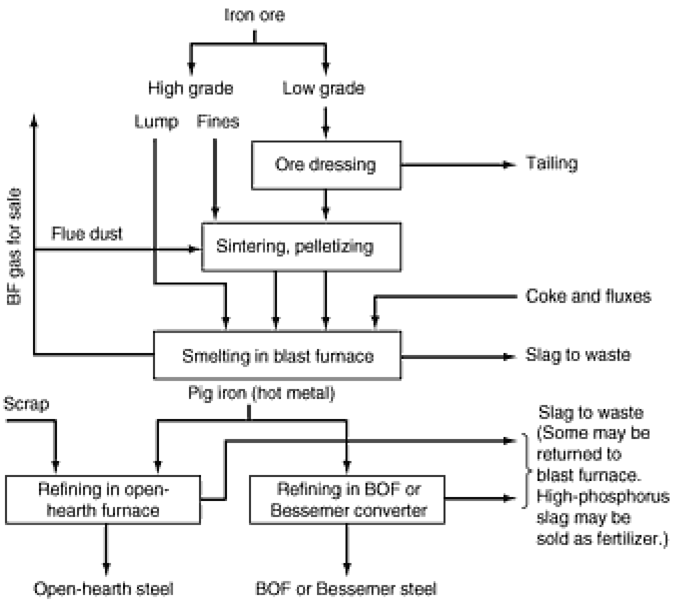
Iron ore
High grade
Low grade
Lump
Fines
Ore dressing
Tailing
BF gas for sale
Flue dust
Sintering, pelletizing
Coke and fluxes
Smelting in blast furnace
Slag to waste
Pig iron (hot metal)
Scrap
Refining in open-hearth furnace
Refining in BOF or Bessemer converter
Slag to waste (Some may be returned to blast furnace. High-phosphorus slag may be sold as fertilizer.)
Open-hearth steel
BOF or Bessemer steel

Fig. 4 Flow diagram for ironmaking and steelmaking through open-hearth and oxygen-steelmaking routes. BOF, basic oxygen furnace

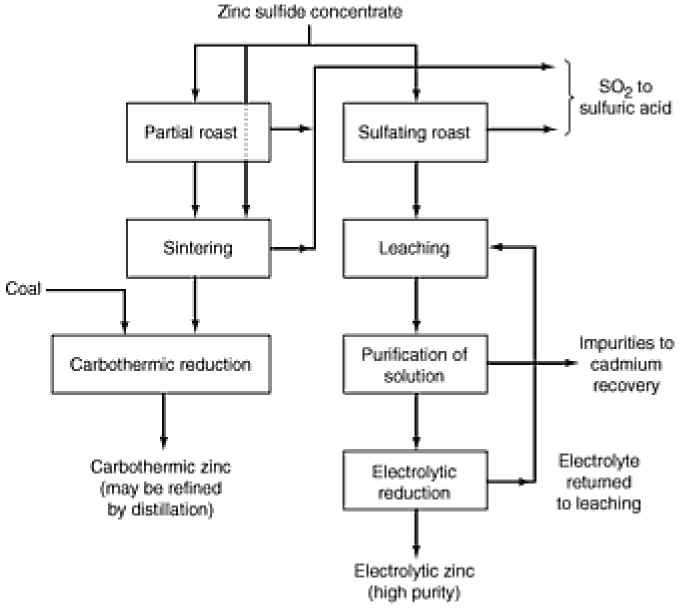
Zinc sulfide concentrate
SO_2 to sulfuric acid
Partial roast
Sulfating roast
Sintering
Leaching
Coal
Carbothermic reduction
Purification of solution
Impurities to cadmium recovery
Carbothermic zinc (may be refined by distillation)
Electrolytic reduction
Electrolyte returned to leaching
Electrolytic zinc (high purity)

Fig. 5 Production of zinc from zinc sulfide concentrate

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Pyrometallurgical Processes

The mineral concentrate produced from crude mined ores is a complex mixture of minerals and some residual gangue and is usually not suitable for direct reduction. Notable exceptions are the direct reduction of iron or the iron-carbide process, which rely on an ore feed of very high-purity iron oxide (that is, containing a very small amount of associated gangue). Some preliminary treatment is necessary depending on the reactivity of the major metal. The ore concentrate of highly reactive metals, such as aluminum, magnesium, titanium, and calcium, must be pretreated to get a high-purity feed, which would yield a high-purity metal upon reduction because the refining of reactive metals is difficult. In some cases, a pretreatment is necessitated by the fact that the concentrate is a rich source of not just one metal compound, but two or three. On the other hand, the raw feed for production of low-reactive metals, such as iron, chromium, and nickel, is not pretreated extensively; hence, upon reduction it results in an impure metal requiring subsequent refining. Therefore, before the primary reduction occurs, ore concentrate needs to be prepared.

Preparation Processes

The pyrometallurgical pretreatments include drying, calcination, roasting to oxides or sulfates, reduction roasting, chlorination or carbo-chlorination, and other exotic processes.

Drying. The objective of drying operations is the removal of bulk water and volatiles, which together usually comprise 20 to 30 vol%. This evaporation of water can be accomplished either by heating the solid material or by using a vacuum system. Vacuum systems are used in the removal of organics that would decompose at high temperatures. The percent of weight lost is known as *loss on ignition* (LOI). Sufficient time at temperature must be allowed for complete drying. Because the evaporation of water is endothermic (the heat of vaporization of water is 44 kJ/mol), energy must be supplied for the evaporation of water as well as to bring the material up to drying temperature. Drying is conducted at temperatures close to the boiling point of water, which allows the use of low-quality fuels, such as hot combustion gases from other processes or cheap producer-gas fuel. Also, the low temperature used for the drying process puts no special demand on the equipment material.

Fixed-bed furnaces, rotary kilns, and fluidized-bed furnaces are commonly used for drying. Fixed-bed furnaces or shaft furnaces are most suitable for drying coarse materials. Rotary kilns are usually used with feed material of a mixed size. Fluidized-bed furnaces are used for drying predominantly fine-grained material. If the concentrate is to be roasted on multihearth roasters, drying and preheating occur on the upper hearths utilizing the ascending heat from the roasting hearths. Some flash roasters also dry the concentrate on the upper hearths, take it out, grind it to eliminate lumps, and then inject the fine, dry material into the combustion chamber. Wet concentrates can be fed into a fluid-bed roaster, and they rapidly dry in the hot, turbulent bed. Wet concentrates can also be fed into reverberatory furnaces as long as the feed does not build up on the sides of the furnace and then drop into the hot bath causing explosions. A separate drying step is usually expensive. In most reactors, drying occurs as the charge is descending or waiting for the final roasting, reduction, or smelting process.

Calcination is a high-temperature operation used for removal of chemically bound water or for decomposition of carbonates to remove carbon-dioxide gas. The most common example of calcination in the metallurgical industry is the decomposition of metal carbonates to form metal oxides, such as lime from limestone. In one atmosphere, the temperatures required for decomposition of carbonates or hydroxides range from 1000 to 1500 °C (1832 to 2732 °F). A typical decomposition reaction at 1000 °C (1832 °F) and 1 atm pressure is:

$$CaCO_{3(s)} \leftrightarrow CaO_{(s)} + CO_{2(g)} \quad \textbf{(Eq 1)}$$

The rate of decomposition is a function of the heat input (Ref 9) because calcination is a gas-solid reaction, and the rate of the process is controlled by conduction of heat through the product oxide layer. To increase calcination rates in industrial furnaces, a large amount of excess heat is commonly used. The excess heat increases the calcination rate, but it also causes rather high temperatures in the oxide-product layer. Calcium oxide, which sinters readily at temperatures just above the calcination temperature, has lower pore volume, specific surface area, and reactivity if excess heat is used (Ref 10).

Fixed-bed or shaft furnaces are commonly used for calcination of lump carbonate material. However, because of the long residence times and high surface temperatures, the oxide products tend to be less reactive, or *hard-burned.* Rotary kilns produce oxides that are more reactive, or *soft-burned,* but have lower fuel efficiency and higher maintenance, operation, and capital costs than the shaft furnaces. Like drying, calcination is also achieved as a part of the primary metallurgical process of roasting or prereduction.

Roasting is the process in which the mineral mixtures are heated to temperatures just below the melting or sintering point of the mineral in the presence of air or other reactive gas to achieve a chemical change. Roasting is a prominent step in the extraction of copper. Common roasting temperatures are between 500 and 900 °C (932 and 1652 °F), where reaction kinetics are fast. The roasting process is carried out by contacting the sulfide with air at elevated temperatures. Once the roasting has started it is autogenous, that is, no external fuel is required, because of the exothermicity of the roasting reactions. The burning of the sulfides often provides more heat than required to self-sustain the process.

The equilibrium relationships of the metal-oxygen-sulfur system are used to determine which solid phase, metal, oxide, sulfide, or sulfate will be present as a product. It is possible to show the equilibrium relationships of the system on a predominance area diagram. See Fig. 6 for Cu-O-S and Fe-O-S systems at 700 °C (1292 °F) (Ref 11). Specifying two gas compositions, such as oxygen and sulfur dioxide, fix the stable solid phases possible. Partial pressure of sulfur or sulfur trioxide gas could also be used as one of the axes on the graph. Generally, pyrometallurgical plants seek to produce oxides from sulfides during roasting for subsequent reduction by carbon or other reducing agents. Production of sulfates by roasting would be desirable if subsequent leaching (hydrometallurgical process) were to take place. The production of metal directly in roasting is a phenomenon observed in sinter-roasting of lead concentrates.

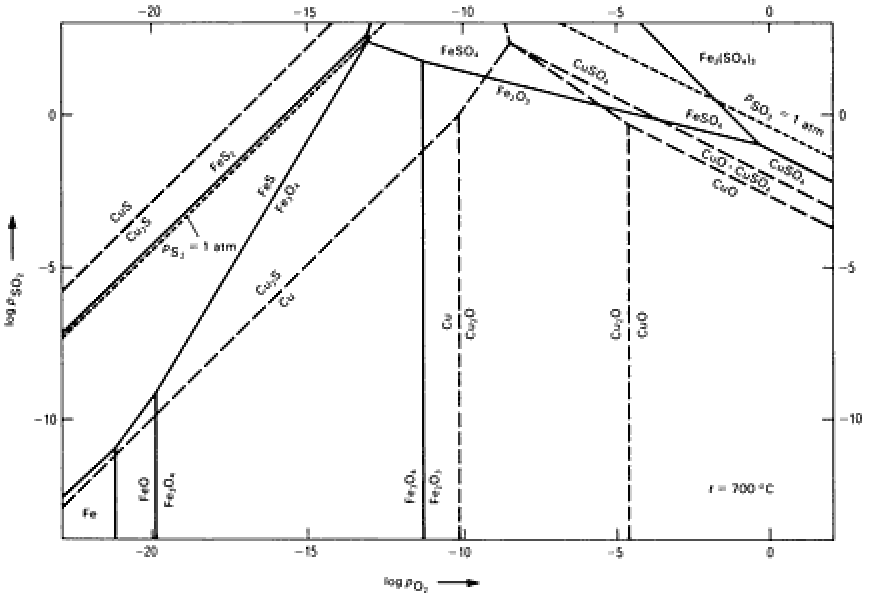

Fig. 6 Predominance area diagram for roasting of iron and copper sulfides at 700 °C (1292 °F). Solid lines: iron compounds. Dashed lines: copper compounds. Dotted lines: gases. Ternary compounds are disregarded.

As mentioned earlier, roasting in a reducing atmosphere is normally used for partial reduction, such as the conversion of Fe_2O_3 to Fe_3O_4 for subsequent magnetic separation. Roasting in a chlorine atmosphere or in the presence of chlorides is a method for producing metal chlorides from metal oxides, which can then be volatilized or leached. Addition of carbon is sometimes necessary during chlorination for thermo-dynamic considerations when the oxide is more stable than chlorides under normal temperature conditions.

Modern roasters are equipped with temperature control, atmosphere control, and heat conservation devices. In addition, provisions are made for greater exposure of mineral surfaces to the gas by frequent rabbling or by dispersion of the solids into a particle/gas suspension. Modern equipment is limited to multihearth, flash, and fluidized-bed roasters. Multihearth roasters are cylindrical in plan with 4 to 12 superimposed hearths. The feed enters at the top and is rabbled first to the center, where it drops to the second hearth to be rabbled to the outer edge, where it drops to the third hearth. The process continues until the roasted material exits from the bottom hearth of the roaster. The gases rise countercurrent to the material movement and are usually removed at the second hearth and sent to flues, dust collectors, or possibly an acid plant. The rising gas also dries the descending charge.

A flash roaster has a larger capacity than a multihearth roaster of similar dimensions because exposure of mineral surfaces to the reacting gas is greater. The top-injected charge gets dried and preheated before free-falling through the combustion chamber where rapid oxidation occurs. In later models the drying hearths are at the bottom of the cylindrical structure. A fluid-bed roaster reverses the concept of a flash roaster by blowing the gases through a turbulent bed of mineral particles. The charge is lifted up by the gas pressure, which expands the bed and allows more intimate contact between the gas and the fine material.

Sintering. The process used to cause partial reduction and agglomeration of relatively fine ore concentrate is known as sintering. In sintering, high temperature is used to obtain partial fusion of particles to form a *sinter.* Sintering is an integral part of the modern day ironmaking. Sintering of iron ore concentrates results in the coalescence of small particles into larger prereduced prefluxed agglomerates that will not blow out of the furnace. Drying, calcining, and roasting are simultaneously achieved. Sintering of nonferrous sulfide concentrates of lead, copper, zinc, and other metals has the dual function of particle-size control and simultaneous roasting, but the roasting is of even more importance because the final sulfur content may be critical.

A sintering machine comprises a grate on which the charge is spread and then ignited. Air is either blown up through the grate and the bed or sucked down through the bed and grate. High-sulfide ores generate enough heat to reach the temperature needed for sintering. Low-sulfur ores or iron ores with no fuel value require fuel additions usually in the form of carbon (coke breeze). Continuous sintering machines can be controlled to a greater extent and also simplify feeding of the charge and discharging of the finished sinter. Most continuous sintering machines run on a downdraft principle; however, in lead smelting, the updraft sintering makes a sinter with higher lead content and eliminates most of the windbox lead. The properties of a sinter are critical to the operation of the smelter, that is, the iron blast furnace. These properties are related to the sinter charge composition, sizes of the constituents, sintering temperature, grate speed, and suction velocity.

Sinter-roasting is the customary method of preparing feed for lead blast furnaces, and in rare cases, for copper blast furnaces. It is also the method for treating zinc sulfide concentrates before smelting either in electrothermic furnaces or in the imperial smelting furnace.

Pyrometallurgical Reduction

The metal content in ore concentrates after preparatory processes is mostly in the form of metal oxides or sulfides in much higher concentrations than the original ore; thus it is suitable for reduction and smelting into the desired metal product. This procedure can be represented by the general equation:

$$\mathrm{MX} + \mathrm{R} \leftrightarrow \mathrm{M} + \mathrm{RX} \qquad \textbf{(Eq 2)}$$

where M is any metal, X is the nonmetallic element or elements originally combined with M, and RX is the reaction product. When the metal compound, MX, decomposes at moderately high temperatures with or without air to yield the metallic element, the reducing agent, R, may not be required. This is the case in the heating of mercuric sulfide (cinnabar) in air to yield mercury and sulfur dioxide as it is during the thermal decomposition of zirconium and hafnium tetraiodide to produce the metals.

Reducing Agents. Figures 7 and 8 show the important Ellingham-Richardson diagrams for the metal-metal oxide and metal-metal sulfide systems, respectively. These equilibrium diagrams--along with the vapor-phase diagrams and the isothermal stability or predominance area diagrams for various metal(s)-non-metal(s) systems (Ref 12)--form the basis for selecting the appropriate reducing agent in pyrometallurgy. The thermodynamic principles for the generation of these graphs have been fully described in Ref 13 and 14. Such processing conditions need to be created where the metal is stable on these diagrams.

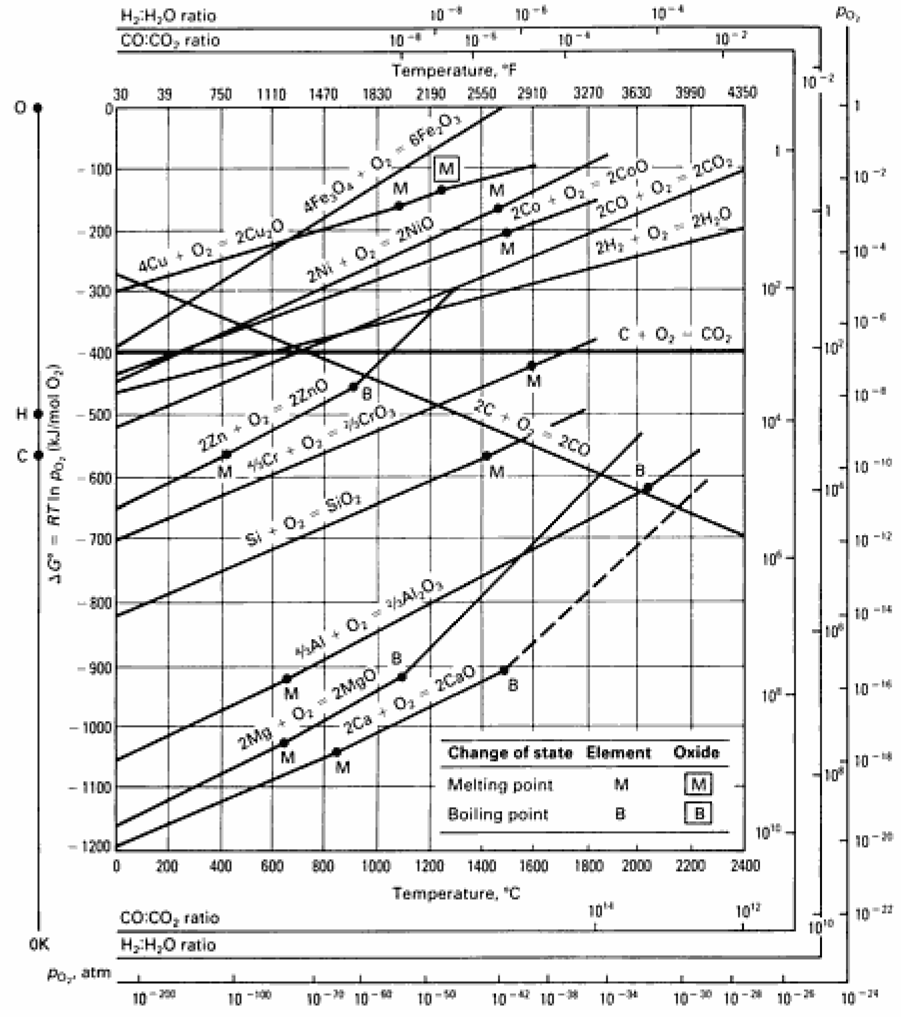

Fig. 7 Ellingham-Richardson diagram showing standard free energy of formation as a function of temperature for metal oxide systems

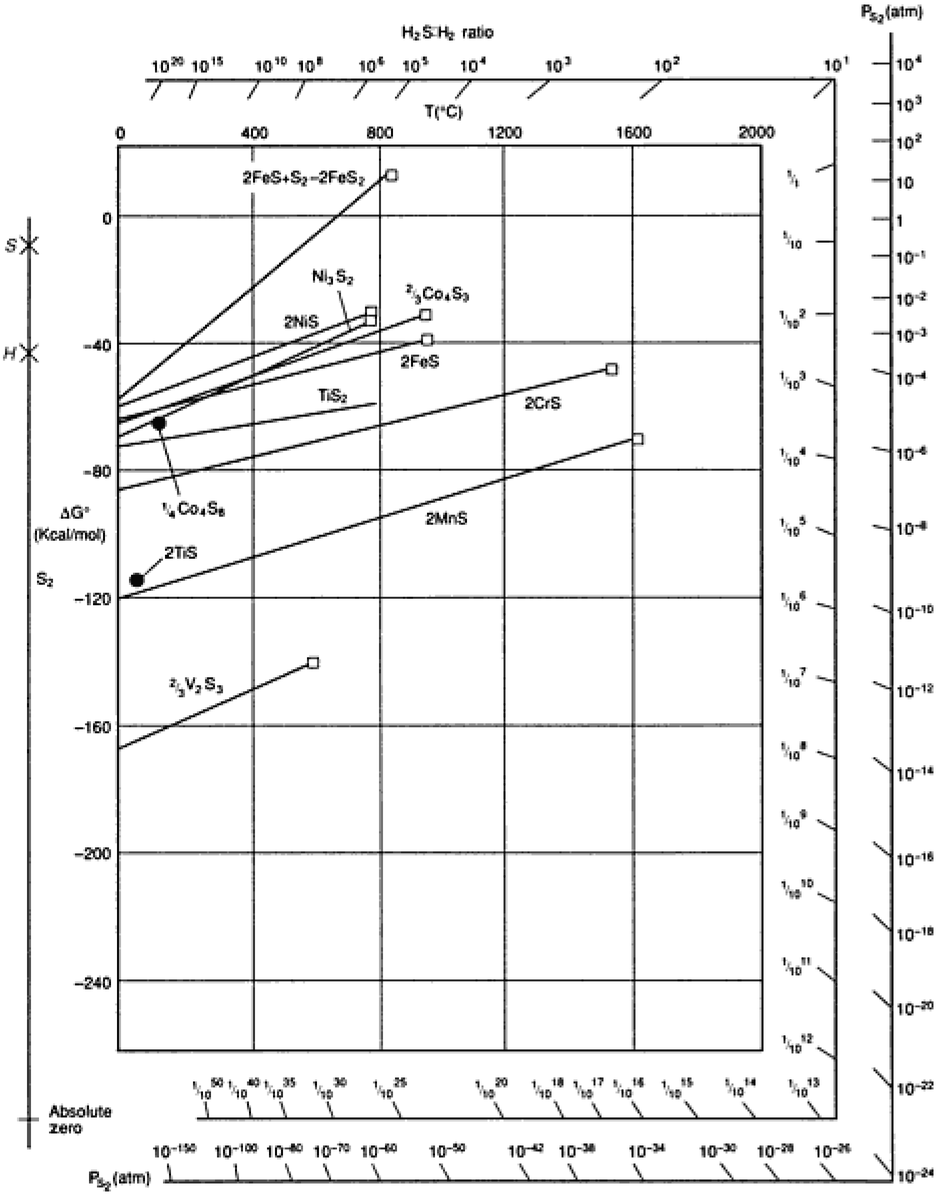

Fig. 8 Ellingham-Richardson diagram showing standard free energy of formation as a function of temperature for metal sulfide systems

Figure 7 is a plot of the standard free-energy change for metal oxide formation as a function of temperature. The relative positions of the individual lines on this plot show the relative tendency of the metal to form the oxide. Following Fig. 7 from top to bottom reveals an increase in tendency to form an oxide for the metal because a higher negative change in free energy (a desired state due to higher stability) is indicated. In other words, the oxides at the bottom of the plot are stable and, therefore, are more difficult to reduce to the element. Since the standard free energy change decreases with an increase in temperature, it is easier to reduce at a higher temperature. For a given line, the metal is stable below and the metal oxide is stable above the line. It should be noted that all the lines are plotted for one mole of oxygen gas, which allows for a ready comparison of different metal oxide stabilities. Figure 7 shows which metals would preferentially oxidize if several pure metals were exposed to the same amount of oxygen (activity or partial pressure) in the environment. For example, if iron and aluminum are exposed to ambient air at high temperature, aluminum will preferentially oxidize. It is easy to determine the partial pressure of oxygen at any temperature below which metal would be stable.

The oxygen potentials of the reducing gas mixtures of CO/CO_2 and H_2/H_2O can also be determined, which indicate the reducing ability of an oxide by CO or H_2 atmospheres, respectively. Some other important lines in Fig. 7 are the carbon, carbon monoxide, and hydrogen stabilities because these are the most common reducing agents in pyrometallurgy. These processes are known as carbothermal or hydrothermal reduction. These reducing agents are stable below their respective lines; therefore, they cannot reduce an oxide that is below it. For example, carbon cannot reduce alumina at reasonable temperature conditions. It can be readily seen that the relative stabilities of oxides can change as a function of temperature, making such a reduction feasible at very high temperature. Likewise, the principle of metallothermic reduction can be appreciated. A metal with the tendency to form a more stable oxide can reduce a less stable oxide. For example, magnesium can reduce silica or titania. On a practical note, while carbon and hydrogen produce gases upon reduction, metallothermic reductions usually result in a solid oxide product, which can pose serious kinetic concerns, forcing the reduction reaction to completely seize. For example, if calcium metal is used to reduce a less stable metal oxide, the resultant calcium oxide must be fluxed off or the reaction will stop. This can apply in comparing the behavior of two compounds of the same metal. Figures 7 and 8 can be compared to evaluate the relative stabilities of a metal oxide and a sulfide, that is, the compound with a higher negative free energy change is more stable. In certain cases, reduction of metal from metal compounds can be achieved. For example, lead can be produced by reacting lead oxide and lead sulfide at a temperature where sulfur dioxide is more stable than the metal compounds combined.

Using the Ellingham-Richardson or any other equilibrium diagram requires caution. These diagrams provide no knowledge about the reaction kinetics. Rarely the case in a real system, standard states (unit activities) are assumed for elements and their compounds. Pyrophorocity of fine metal powders or the passivating effects of a compound are ignored in determining reactivities. Possible reactions between the elements are also not considered in the thermodynamic analysis. Free energy change data for individual compounds are also quite different. This must be kept in mind when selecting the reducing agent for pyrometallurgical treatments for metal compound reduction. In addition to the theoretical thermodynamic bases, cost, the nature of the reaction by-product, the solubility of the reducing agent in the metal produced, and the possibility of reaction of the metal with the reducing agent should also be considered when selecting a reduction agent.

Carbon is a relatively cheap reductant, which has to be carbonized or converted into coke for strength and reducibility. The resulting CO/CO_2 by-product escapes from the reacting mass, and the change in the standard free energy of the reaction given in Eq 2 with carbon as the agent becomes more negative with increasing temperature. Most compounds in Fig. 7 and 8 show a less negative free energy change with increasing temperature. This means that even the most refractory oxides will be decomposed by carbon if the mixture is heated to a high enough temperature. The drawbacks of using carbon as the reductant are that the metal is usually a strong carbide former and reacts with carbon to yield an impure metal at high temperatures, for example, it produces pig-iron in blast furnaces with 4 to 5 wt.% carbon in solution. A low-temperature process can lower the amount of carbon that can join the reduced iron. Molybdenum, tungsten, and vanadium are also produced with appreciable carbon contents if reduced from mixtures of metal oxide and carbon. A high temperature is required to separate the balance gangue in the ore calling for smelting temperatures rather than plain solid-state reduction. Carbon may also be able to reduce some of the other compounds present in the gangue.

If oxygen is soluble in the metal being produced, the activity of the oxygen is reduced such that the most effective reducing conditions cannot reduce the oxygen content below an equilibrium condition. This interferes particularly for titanium and zirconium, which cannot be reduced from their respective oxides using carbon to obtain a low enough oxide content for commercial requirements.

Hydrogen can be used to reduce metal oxides if carbon reduction is not suitable due to carbide stability or oxygen activity in equilibrium with carbonaceous gases; for example, tungsten oxide may be reduced by hydrogen to meet performance specifications. The cost of hydrogen will be higher than carbon if the metal oxide has a large negative free energy of formation, which in turn would lead to an equilibrium composition of the reaction gas high in hydrogen and low in water vapor. In this case, the moisture content of the reaction gas must be reduced prior to recirculation.

An example of a metallothermic reduction of an oxide with another metal having a greater affinity for oxygen is the Goldschmidt reaction. In this reaction, iron oxide mixed with aluminum powder produces a molten iron and a cloud of finely divided alumina. Vacuum reduction of calcined dolomite with ferrosilicon depends on the magnesium oxide being reduced by the silicon, followed by the reaction of the resulting silica with calcium oxide content of the calcined dolomite to form a calcium silicate, thus avoiding reaction of some of the magnesium oxide (MgO) with silica. Note that straight reduction of MgO with silicon is not feasible (Fig. 7). In general, the reduction of metal oxides with other metals is adopted only when carbon or hydrogen cannot be used due to thermodynamic considerations. Metallic reductants are generally expensive and tend to form an intermetallic alloy with the reduced metal.

Reduction of Nonoxide Compounds. Nonferrous metals that occur as sulfides also require direct reduction. Separation concerns similar to those about oxides exist for sulfide reduction, due to the presence of gangue and the possibility of simultaneous reduction of two metal sulfides. Metal oxides such as uranium, titanium, or zirconium oxides

(UO_2, TiO_2, and ZO_2 respectively) that, due to low oxygen activity, do not yield all of their oxygen even to strong reducing agents, have to be reduced from their halides with calcium, lithium, sodium, or magnesium, which are stronger halide formers than the refractory metals. Conversion of oxides into chlorides prior to thermal reduction can occur by chlorination or by carbo-chlorination. Note that the reaction shown below in Eq 3 is not feasible under lower temperatures, but the reaction shown in Eq 4 is. Similar reactions occur with zirconium.

$$TiO_2 + 2Cl_2 \leftrightarrow TiCl_4 + O_2 \ (+)\ \Delta G^\circ \quad \textbf{(Eq 3)}$$

$$TiO_2 + C + 2Cl_2 \leftrightarrow TiCl_4 + CO_2 \ (-)\ \Delta G^\circ \quad \textbf{(Eq 4)}$$

Alternatively, metal can be produced by reacting two metal compounds, such as lead oxide and lead sulfide. First, there is a roasting reaction in air where lead oxide and lead sulfate are produced, followed by a reaction between these oxidation products and some of the remaining lead sulfide to produce metallic lead and SO_2 gas:

$$2PbO + PbS \leftrightarrow 3Pb + SO_2 \quad \textbf{(Eq 5)}$$

The reaction in Eq 5 requires that the free energy of formation of SO_2 must exceed the free energy required to decompose the lead oxide and the lead sulfide. This reaction is not commercially practiced. Copper converting utilizes the same sequence of partial oxidation followed by reaction to produce blister copper from copper matte (Ref 6). Conversion of copper sulfide is conducted at temperatures high enough so that all constituents are liquid and the reactions are rapid. Similarly, nickel sulfide can be converted to metallic nickel by using high temperatures, which can be achieved in a top-blown converter using oxygen.

Slags. The reduction reactions on impure metal ores usually require formation of a slag to dispose the gangue material in the feed. For example, Fe_2O_3 reduced with carbon yields impure metallic liquid iron and a CO/CO_2 mixture that can escape from the furnace. However, the accompanying gangue comprising alumina, silica, magnesia, and others must be converted to a form that melts and is separable. This molten liquid of oxides is the slag. Sometimes, it is preferable to add fluxes, such as calcined lime, which will react with the gangue to produce a fluid slag. Other desirable features of the slag are low melting point, low viscosity, low tendency to react with refractories or to dissolve the metal, and low density to obtain good separation. Since slags do not have appreciable utility, they must also be of low value. If the gangue is primarily acidic, basic fluxes are required as opposed to a basic gangue which can be neutralized by an acidic flux.

Pyrometallurgical Process Equipment

Reverberatory furnaces comprise a large rectangular refractory-lined hearth area and an arched roof. These furnaces are gas, oil, or coal fired where combustion occurring in the furnace space "reverberates" the heat off the roof down onto the hearth. Reverberatory furnaces are commonly used for matte smelting of finely divided copper sulfide concentrates. However, reduction of liquid baths by charcoal or coke is difficult because slag often prevents contact with the bath. Recent advances in process control and refractory development allow the blowing of mixtures of gases through protected tuyeres submerged in the bath or by top blowing. These furnaces can be of the reverberatory type or can be more like kilns with a mechanism for partial rotation.

Blast furnaces are used for reducing the metal oxides that are not highly reactive, such as iron, zinc, and lead. The size and shape of the blast furnace differs for different metals. The iron blast furnace operation has been described in the article "Steelmaking Practices and Their Influence on Properties" in this Handbook. In short, it consists of continuously charging the solid material from the top and blowing hot air from the bottom, causing a counter current flow of solid and gas where heat is exchanged. Air oxidizes carbon in the coke to carbon monoxide, which reduces the oxides of iron through various oxidation states. The reduced iron melts in the hearth and, as the heavier liquid, rests under the layer of molten slag, which consists of unreduced oxides from the gangue. Slag melting occurs with the assistance of appropriate flux addition. A typical product from the iron blast furnace has the chemical composition of 4% C, 0.8 to 2% Si, 0.01 to 0.03% S, 0.3 to 0.5% P, and some manganese depending on the content of the feed material.

Lead blast furnaces are much smaller than iron blast furnaces because of the lower volume of material treated at a lead smelter. The cross-sectional plan of the lead furnace is rectangular rather than circular to allow the penetration of low-pressure blast to the center of the charge. The furnace is top-charged with lead sinter, which also contains most of the fluxes and coke to adjust the final slag composition. As the charge descends in the shaft it moves counter-current to the ascending hot reducing gas generated by the combustion of coke in the tuyere zone, similar to the iron operation. The charge is dried, the carbonates are calcined, and the metal oxides are reduced by the carbon monoxide (CO) in the gases as the descending charge gets hotter. At the same time, the siliceous gangue reacts with the lime and iron oxide flux to form droplets of slag. Finally, the whole charge is melted with the molten lead on the bottom of the crucible and the slag floating on the lead. The residual sulfur in the charge combines with copper, iron, and lead to form an artificial mixture of sulfides known as matte. Usually this matte is sold to the copper smelter as it contains precious metals as well. Both slag and metal are tapped continuously into a forehearth where the slag overflows and the lead accumulates to be tapped periodically.

Copper blast furnaces are similar to lead furnaces but are not prevalently the equipment of choice. Reduction of copper oxide in a blast furnace is accompanied by simultaneous reduction of some of the iron oxide in the charge, yielding a mixed iron-copper alloy referred to as black copper. If reducing conditions are made less intense in the furnace to avoid iron contamination, more copper is lost through the slag.

Imperial furnace or lead-zinc blast furnace smelting of zinc oxide requires that the gas mixture be kept at a high enough temperature to prevent the oxidation of zinc. The imperial furnace has no cold zones, the charge is preheated before entering the furnace, and the gases are kept hot in the condensers. The zinc is captured from the gas mixture by absorption on small drops of liquid lead created by violent mixing of a lead bath in the condenser. Subsequent cooling of the zinc-lead alloy yields two immiscible liquid layers: the upper one high in zinc, which can be sent to a refining column, and the lower one high in lead, which is recirculated to the condenser. If the furnace is fed a mixture of lead and zinc oxides, the lead can be reduced and tapped from the furnace while the zinc vapors issued from the upper part of the furnace move to the condenser. The lead reduction does not require an additional reducing agent.

Converters are essentially refractory-lined vessels holding a molten bath of metal or metal sulfide into which air or oxygen can be blown to achieve rapid oxidation and refining. The shape and construction depend on the material to be treated. Converters are the equipment of choice for making steel from pig iron and are described in the article "Steelmaking Practices and Their Influence on Properties" in this Handbook. Copper refining uses a side-blown converter with provision for tuyere punching, which is known as the Pierce-Smith converter.

Electric furnaces of direct and indirect arc types, as well induction melters, have fast become the most used equipment for pyrometallurgical processes for pure metals and alloys production, as well as for melt refining. The source of energy is mostly electrical and external, since little exothermic process heat is realized in these furnaces. Electric-arc furnaces are also very popular for melting and refining recyclable scrap metals. A schematic of the electric-arc furnace is shown in this Handbook in the article "Steelmaking Practices and Their Influence on Properties."

Retorts are used to produce metals that can only be reduced at temperatures above their vaporization points so that these metals emerge from the reacting mass in the vapor state and require condensation. For example, a zinc oxide and carbon mixture is smelted in horizontal retorts, which are refractory cylinders closed at one end and heated from the outside. The charge of oxide sinter and coke or coal is charged from the open end, which is then closed with a refractory condenser. Upon heating, the zinc vapors and CO enter the condenser where the temperature is lowered to condense the vapors to liquid zinc. Due to its lower operating cost, the vertical retort process has replaced horizontal retort furnaces. Vertical units are much larger with semicontinuous operation utilizing periodic feeding of hot batches of sinter and coke. The vapors are condensed in a large spray condenser and the zinc is tapped periodically. Production of magnesium by the reduction of calcined dolomite with ferrosilicon is also carried out in alloy steel retorts. A vacuum is maintained in the retort to assist migration of the magnesium vapor to the cold zone where the metal condenses as solid "muff" of magnesium.

Pyrometallurgical Refining

Thermodynamic conditions prevailing in pyrometallurgical reduction processes and the constituency of the charge material do not allow selective preparation of a pure metal through direct smelting. In addition, the reducing agent and the vessel lining add to the contamination of the metal produced. The purpose of refining, therefore, is to remove various impurities until the metal can meet the purity specifications.

Liquation is the process where impurities are frozen out by reducing the temperature of the bath. For example, in a binary alloy system of gold and silver showing a continuous solid solution, cooling the melt will freeze out an alloy higher in gold (higher melting-point element). Subsequent treatment is required since there is no clear separation of the two metals. In the lead-silver eutectic system, cooling the mixture freezes out almost pure lead. Alloy systems that form two immiscible layers upon cooling, such as lead-zinc, can be used to yield two usable products, as described in the imperial furnace discussion.

Refining with gaseous reagents is the method for effective and selective removal of impurities using solid and gaseous reagents. Refining with oxygen presumes that the impurity is more readily oxidized than the host metal and that the resulting impurity oxide is not soluble in the host metal. Removal of silicon, manganese, carbon, and phosphorus from pig iron to produce steel is the best example of the use of oxygen gas for refinement. Resulting oxides combine with lime to form a fluid removable slag. High-temperature oxidation of impure lead by injection of air into a molten bath eliminates arsenic, antimony, and tin as oxides which combine with PbO to form a slag. This process is selective: gold, silver, and bismuth are not oxidized.

In copper converting, the resulting blister copper carries some iron and sulfur, which are eliminated by fire refining process where air is blown into the molten blister and the remaining iron and sulfur are oxidized. Silica sand is added to the bath to react with iron oxide and form a slag. The slag contains a high amount of copper, which is returned to the process for its recovery. Oxidation can be achieved with air, oxygen, or steam injections. These represent oxygen at different activities and may be the basis for obtaining more selectivity in oxidation.

Although zinc can be selectively oxidized from molten lead by air injection, a fairly high temperature is necessary, and the mixed zinc-lead oxide skimmings are not easily treated. However, removal of zinc as a chloride can be achieved at a lower temperature by injecting chlorine gas into the lead-zinc alloy in a closed kettle. The mixed chloride slag may also undergo commercial processing for further recovery. In a similar way, iodine can be reacted with impure titanium, zirconium, or hafnium to form a volatile iodide that leaves the impurities behind. The volatile iodide is brought into contact with a hot filament which decomposes the iodide, leaves the pure metal to deposit on the filament, and releases the iodine to return and react again with the feed metal.

Application of solid reagents for impurity removal depends on their ability to react selectively with the impurities and to form an insoluble phase that can be removed from the parent metal. Common examples are additions of sulfur to remove copper from lead, additions of zinc to remove gold and silver from lead, and additions of calcium and magnesium to remove bismuth from lead.

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Hydrometallurgical Processes

Similar to pyrometallurgical processing, hydrometallurgy may not be directly applicable without a pretreatment. Drying, calcination, and roasting, as discussed previously, may be required to upgrade the ore and prepare it for hydrometallurgical processing. The hydrometallurgical steps may be broadly classified into leaching, purification and metal deposition using aqueous solutions. Although these process steps are predominantly conducted at ambient temperatures, higher temperatures near the boiling point of water or above it (as in pressure leaching) may be necessary for faster kinetics. It should be noted that the same thermodynamic principles apply here as have been discussed for molten metals and slags.

Leaching Processes

Leaching is a separation process that uses aqueous solutions. A suitable aqueous environment is selected which can decompose the mineral containing the valuable metal. The objectives of leaching are:

- Production of a compound for further processing by pyrometallurgical techniques
- Production of a metal from impure metal or metal compounds that have been prepared by a pyrometallurgical process
- Direct production of a metal from an ore or concentrate

Selection of a particular objective depends on economic factors and the involved thermodynamic and kinetic conditions of the system. The theoretical possibility is limited by thermodynamic constraints, whereas kinetic constraints relate to the overall time required and affect the reactor size and design.

The thermodynamics of leaching are concerned with the ability to decompose a particular compound so that it will selectively dissolve and become stable in the aqueous solution used for leaching. Proper calculations can predict the maximum amount of mineral that can be leached until the system reaches equilibrium. The rate of dissociation and dissolution is kinetically controlled. Figures 9 and 10 are schematic diagrams of a mineral/water interface on a microscopic scale. The concentration of the active chemical in the bulk of the solution is greater than the concentration near the surface of the mineral. This occurs because the active chemical is removed from solution by reaction at the mineral surface. Figure 9 shows that the rate at which the reaction or decomposition of the mineral will occur is determined by: (1) the diffusion of reactant, R, from the bulk of the solution to the surface of the mineral; (2) the reaction of the reagent with the surface to form a soluble species; and finally, (3) the diffusion of the product metal species, M, away from the surface. In Fig. 10, diffusion of R through the porous product layer and diffusion of M through the product layer are also possible (Ref 15).

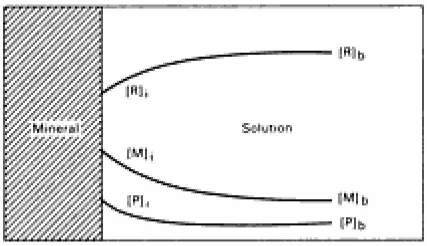

Fig. 9 Schematic diagram of a mineral surface showing complete dissolution in water

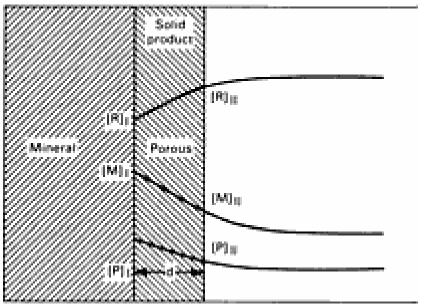

Fig. 10 Schematic diagram of a mineral surface showing decomposition in water and generation of a porous layer of residue on the surface

The leaching of a compound in an aqueous environment can take several forms. Simple dissolution reactions in water, acid, and alkali can be represented by Eq 6, 7, and 8 respectively:

$$CuSO_{4(s)} + nH_2O \leftrightarrow CuSO_4 \cdot nH_2O_{(aq)}$$ **(Eq 6)**

$$ZnO_{(s)} + 2H^+_{(aq)} \leftrightarrow Zn^{2+}_{(aq)} + H_2O$$ **(Eq 7)**

$$Al_2O_{3(s)} + 2OH^-_{(aq)} \leftrightarrow 2AlO^-_{2(aq)} + H_2O$$ **(Eq 8)**

Anionic base exchange, oxidation-reduction, and water-soluble complex formation reactions can be shown by the reactions shown in Eq 9, 10, and 11, respectively:

$$CaWO_{4(s)} + CO^{2-}_{3(aq)} \leftrightarrow CaCO_{3(s)} + WO^{2-}_{4(aq)}$$ **(Eq 9)**

$$CuS_{(s)} + 2Fe^{3+}_{(aq)} \leftrightarrow Cu^{2+}_{(aq)} + 2Fe^{2+}_{(aq)}$$ **(Eq 10)**

$$CuO_{(s)} + 2NH^+_4 + 2NH_3 \leftrightarrow Cu(NH_3)^{2+}_{4(aq)} + H_2O$$ **(Eq 11)**

Oxygen pressure and pH are the most important parameters for determining the chemical properties of aqueous solutions. Predominance area diagrams can be plotted for a metal/H_2O system in the form of a pH/log p_{O_2} diagram showing regimes of stability for the metal, ions, and insoluble metallic compounds, such as hydroxides (Ref 16).

The leaching method used depends on the physical condition of the ore and the inherent mineralogy. Simple leaching processes include in situ leaching, heap leaching, and agitation leaching. In situ leaching refers to mineral dissolution with the ore "in place" underground. In situ leaching is usually done in worked-out stops of high-grade mines, support pillars left behind after mining, or low-grade deposits. This type of treatment requires the surrounding rock to be tight and impermeable to solution flow in order to contain the leaching solution. This process is very time consuming but has low treatment costs, low equipment requirements, low capital costs, and the ability to treat low-grade ores.

The heap-leaching process is similar to in situ leaching since it does not require extensive leaching equipment, such as tanks, slurry pumps, and thickeners; hence, heap leaching requires low capital and maintenance costs. Therefore, the principal feed materials for heap leaching are low-grade ores, ores not amenable to flotation, and discarded waste rock from previous processing with metal values below milling grade. The leachant is sprayed or pumped over a heap of ore. As it percolates through the heap, it dissolves the desirable compounds from the ore. An agglomeration step prior to leaching of the fine ore has shown significant improvement in precious metals recovery (Ref 17).

Agitation leaching is usually used with well-disseminated, fine-grained, high-grade ores. This requires extensive crushing and grinding before leaching in order to expose the solution to the minerals where agitation improves the process kinetics. Because of the extensive amount of equipment required for agitation leaching, recoveries of over 90% and short residence times are requirements of the process. Agitation is accomplished by either bubble action using compressed air or by mechanical agitation using impellers. Pachuka tanks are commonly used in air-agitated leaching processes (Ref 18). When high-intensity agitation is required mechanical agitation with impellers is usually used. Marine propellers produce an axial flow, paddles cause a tangential flow, and turbine impellers produce a combined radial and axial flow pattern (Ref 19).

Pressure leaching is similar to agitation leaching except that the process is done at elevated pressures and temperatures. Agitation leaching under normal pressure is limited to 100 °C (212 °F). As pressure on the solution is raised, the boiling point of water can be elevated. Thus, higher leaching temperatures can be employed by increasing the pressure. Therefore, the main objective of pressure leaching is to enhance the kinetics of metal dissolution by permitting higher operating temperatures and by increasing the solubility of gaseous species that may take part in the leaching reaction. The oxidation of sulfides in aqueous solutions exemplifies the need for increased gas solubility. At atmospheric pressure metal sulfides are insoluble even in strong acidic solutions. Increasing the temperature and pressure of the system increases the solubility of oxygen in solution. The increase in oxygen solubility and temperature causes rapid oxidation of some metal sulfides to sulfates making them soluble in acid solutions. This ability to achieve oxidation in the leaching step by increasing the pressure can eliminate the need for pretreatment steps, such as oxidation roasting of sulfide ores.

Pressure leaching is generally done in a stainless steel or titanium autoclave for high strength and corrosion resistance at higher temperature and pressure. Linings of glass, lead, or refractory brick may be used under severe corrosion conditions. Most autoclaves are equipped with agitators for mixing. Both vertical and horizontal autoclaves are used in hydrometallurgy. The Sherritt-Gordon process (Fig. 11) uses pressure leaching during the production of nickel and cobalt metals (Ref 20).

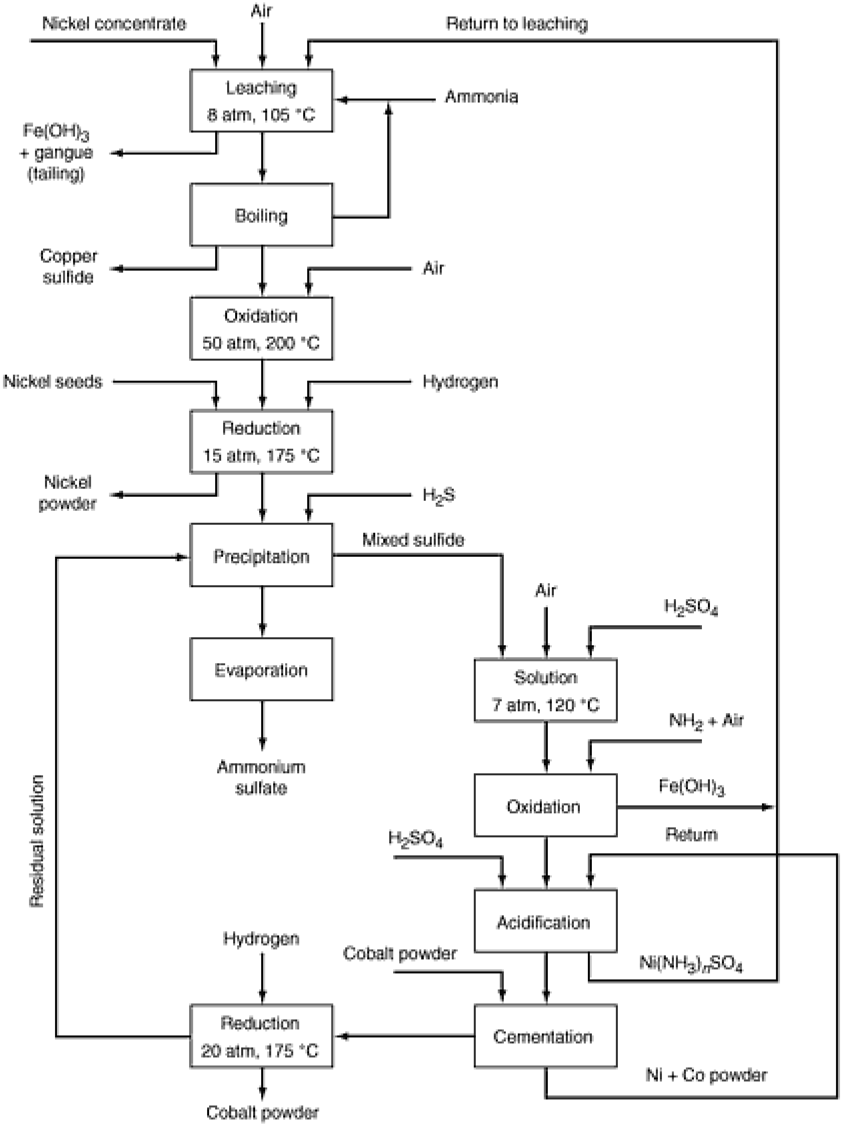
Nickel concentrate
Air
Return to leaching
Leaching
8 atm, 105 °C
Ammonia
$Fe(OH)_3$ + gangue (tailing)
Boiling
Copper sulfide
Air
Oxidation
50 atm, 200 °C
Nickel seeds
Hydrogen
Reduction
15 atm, 175 °C
Nickel powder
H_2S
Precipitation
Mixed sulfide
Air
H_2SO_4
Evaporation
Solution
7 atm, 120 °C
NH_2 + Air
Ammonium sulfate
Residual solution
Oxidation
$Fe(OH)_3$
H_2SO_4
Return
Acidification
Hydrogen
Cobalt powder
$Ni(NH_3)_nSO_4$
Reduction
20 atm, 175 °C
Cementation
Ni + Co powder
Cobalt powder

Fig. 11 Sherritt-Gordon process flow diagram for nickel and cobalt production

Solution Purification

Leaching with strong solutions usually produces an aqueous stream containing the desired metal values as well as some impurities due to the complexity of the mineral ore. Processes for the purification of the leaching solution prior to metal recovery include precipitation, solvent extraction, and ion exchange.

Precipitation involves the removal of ionic species from solution as compounds. Precipitation is accomplished by making adjustments to the solution which cause formation of compounds that are no longer soluble in the solution. The concept of the solubility product is used to predict, and to perform calculations concerning, precipitation from solution. The solubility product for a given compound is defined as the product of the concentrations of cation and anion of the compound of interest, each raised to the power of its proportion in the compound. For example, the solubility product for a hypothetical compound $MX_{2(s)}$ would be

$$[M^{2+}]\,[X^-]^2 = K_s \qquad \textbf{(Eq 12a)}$$

based on the reaction

$$M^{2+} + 2X^- = MX_{2(s)} \qquad \textbf{(Eq 12b)}$$

If the product of the concentrations (left-hand portion of Eq 12a) exceeds the value of the solubility constant (K_s) in a solution, precipitation of the compound occurs.

When used as a purification technique in hydrometallurgy, precipitation can be initiated by one of a few different methods. For example, precipitation can be done by addition of chemicals. If the appropriate cation or anion is added to a solution, it will force the precipitation of a specific compound or compounds by exceeding the solubility products. Because metallic sulfides in general have very small solubility products, addition of sulfide anions (as hydrogen sulfide) causes precipitation of insoluble metal sulfides. Precipitation can also be accomplished by the evaporation of water from the solution. As the water evaporates, the concentrations of all ionic species increase until one or more solubility products are exceeded and precipitation occurs.

Changes in the pH of solutions can also be used to precipitate compounds (Ref 16). As the pH of a solution is increased and the solution becomes more basic, the hydroxide ion (OH^-) concentration increases and solid hydroxides precipitate. Iron, copper, cobalt, and nickel are precipitated selectively as hydroxides in solutions by raising the pH with milk of lime to 2.5, 5.8, 8.3, and 9.4, respectively. Precipitation can be used in a process to remove the impurities as well as to concentrate metal values in the form of a compound. Desired metal values can also be removed from an impure solution and concentrated in a solid compound. The recovery of sulfides of nickel, copper, lead, and zinc from leaching solutions as precipitates requires further purification, but provides a low-cost treatment method with very low concentrations of metal values in the leach solution.

Solvent extraction is a chemical process used to purify and concentrate a given species from aqueous solution. This is accomplished by recycling an organic solution, which selectively exchanges the metal species of interest between an impure aqueous feed solution and a pure fresh aqueous solution. The process relies on the immiscibilities of organic and aqueous solutions as well as the stabilities of the metal species in them. Purification is then achieved by extracting a metal species from the impure aqueous solution to the organic solution and then stripping the metal species from the organic solution back to fresh aqueous solution. A typical solvent-extraction flow sheet is shown in Fig. 12. The organic must be selective to the species being purified, and the reaction must be reversible so that the metal species can be transferred from impure to fresh aqueous solutions via the organic phase. Solvent-extraction chemistry can roughly be separated into two types of reactions: solvation and exchange reactions.

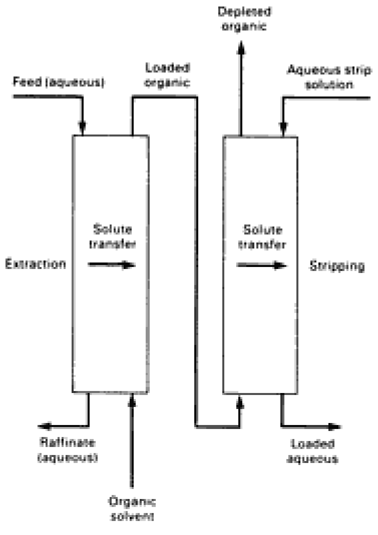

Fig. 12 Typical flow diagram for solvent extraction

Solvation involves transfer of neutral molecular species between aqueous and organic. In the transfer from the aqueous to the organic phase, the neutral species simply dissolves in the organic solution. The organic phases used for solvation can be alcohols, ethers, esters, ketones or phosphorus-containing compounds such as trialkyl phosphates and trialkyl phosphine oxides. Exchange reactions involve the formation of specific bonds between metal species and active compounds in the organic phase. The metal species forms an organic salt with the active organic compounds, which then dissolves in the organic phase. Exchange reactions can be cationic or anionic depending on the system involved (Ref 21).

The organic solutions typically used for exchange reactions are made up of a carrier, an extractant, and a modifier. The carrier or diluent is the inert organic that makes up approximately 90% of the solution and acts as a vehicle for carrying the active extractant. Common diluents are kerosine, and naphthene. The extractant or active agent is the compound that contains the functional group capable of chemically reacting with the particular metal species in the aqueous phase. The modifier, which is usually an alcohol, is added because it increases extracting power, increases selectivity, improves phase separation, and prevents formation of solid organic compounds. Solvent extraction is typically performed in a combination of mixer-settler units to allow the countercurrent flow of organic and aqueous solutions from stage to stage.

Ion exchange is accomplished by interchange of metal ions between aqueous solutions and a solid, insoluble resin. The chemistry of the ion-exchange process is similar to the solvent extraction systems and is sometimes used as a substitute for solvent extraction to avoid problems of emulsion formation and solvent loss due to entrainment. The ion-exchange process involves adsorption followed by elution. Adsorption is the removal of metal ionic species from an aqueous solution when that solution is passed through a bed of ion-exchange resins. Elution is the recovery of the metal ionic species in fresh solution by passing a suitable fresh solution through the previously loaded resins.

Ion-exchange resins are classified as cationic resins and anionic resins. Cationic resins exchange cationic species and are made of strong acid or weak acid groups and exchange H^+ ions. Anionic resins are strong bases, such as quaternary ammonium group bases, and weak bases, such as secondary or tertiary amine group bases. In most cases, chloride ions exchange with anions in solution (Ref 22). The important properties of ion-exchange resins are capacity, selectivity, and mechanical properties. The capacity of a particular resin is the amount of a specific inorganic group that the resin will hold per unit weight or volume. The affinity of a resin for different ions in solution varies. This selectivity of one ion over the other is described as a distribution coefficient, K, where K = (% equivalent of ions in resin)/(% equivalent of ions in solution).

For a particular resin, the selectivity coefficient varies with the species of interest making it possible to purify a particular metal ion from a complex solution. Because ion-exchange resins are used over and over as the transfer media for purification, they require good mechanical properties. Resins must be durable and resistant to breakage, must have low chemical degradation, and must be insoluble in aqueous solutions. The ion-exchange equipment involves fairly high capital costs and a large plant area due to the large amounts of in-process material. However, properly run ion-exchange facilities result in up to 99% efficiency during normal operation.

Metal Deposition

Once an ore concentrate has been leached and purified, the metal of interest must be recovered from solution. Three common techniques of metal reduction from aqueous solution are cementation, hydrogen reduction, and carbon adsorption.

Cementation, or metallic replacement, is a classical process for recovering metals from aqueous solution. Cementation is essentially the precipitation or discharge of a noble or less-reactive metal in favor of a more-reactive metal. The basic reaction between the two metals is electrochemical in nature and can be represented by the reaction in the following equation for the reduction of cadmium by zinc metal:

$$\mathrm{Cd}^{2+}_{(aq)} + \mathrm{Zn}_{(s)} \leftrightarrow \mathrm{Cd}_{(s)} + \mathrm{Zn}^{2+}_{(aq)} \qquad \textbf{(Eq 13)}$$

The above electrochemical reaction can be separated into two half-reactions:

$$\mathrm{Zn}_{(s)} \leftrightarrow \mathrm{Zn}^{2+}_{(aq)} + 2e^- \qquad \textbf{(Eq 13a)}$$

$$Cd^{2+}_{(aq)} + 2e^- \leftrightarrow Cd_{(s)} \quad \textbf{(Eq 13b)}$$

When the active zinc metal is added to a solution containing relatively noble cadmium ions, reduction takes place in microcells producing cadmium metal. Since the two half-cell reactions require transfer of electrons it is essential that the solid is a conductor of electricity. The tendency of one metal to displace or reduce another metal from solution is based on the electromotive series of metals (Ref 23). In general, when two metals are considered, the one that is more electropositive will tend to reduce a less-electropositive metal from solution. Also, the greater the difference in potential between the two metals is, the greater is the driving force for the reaction. However, even a small difference in potential results in an extensive degree of reduction. Reduction of copper ions from solution by metallic iron using cementation is industrially practiced:

$$Cu^{2+}_{(aq)} + Fe_{(s)} \leftrightarrow Cu_{(s)} + Fe^{2+}_{(aq)} \quad \textbf{(Eq 14)}$$

Copper sulfate solution is fed through open launders containing steel scrap where the displacement reaction occurs and produces a very pure copper that can be recovered in the bottom of the launders. Cementation cones are commonly used now for the deposition of metals (Ref 24). The rate at which cementation reactions occur depends on initial concentrations, temperature, agitation, polarization characteristics of different metals, and addition agents (Ref 25).

Gaseous reduction of metals from aqueous solution can be done with reducing gases, such as hydrogen, carbon monoxide, and sulfur dioxide. Hydrogen is the most widely used because it is relatively inexpensive. The reaction products from carbon monoxide and sulfur dioxide have to be further treated after the reduction step. The use of reducing gases also involves a replacement reaction:

$$Cu^{2+}_{(aq)} + H_{2(g)} \leftrightarrow Cu_{(s)} + 2H^{+}_{(aq)} \quad \textbf{(Eq 15)}$$

The tendency of the above reaction to produce copper can be increased by increasing the pressure of hydrogen gas since the reaction moves to the right. A similar reaction for nickel at room temperature and atmospheric pressure does not occur. However, if the reaction is carried out in an autoclave that permits high hydrogen pressures and temperatures, nickel can be reduced from the solution. Although the mechanism by which nickel is reduced from ammoniacal solutions is more complex, nickel is reduced commercially at high temperature and pressure in the presence of ammonia (Ref 20).

Carbon adsorption, or reduction of metals from aqueous solution, is used almost exclusively to recover the noble precious metals, such as gold and silver. This process is based on the principle that these metals can be reduced out of solution by solid carbon at low temperatures and deposited in metallic form on the carbon. In a typical carbon-adsorption process, the metal leaching solution is fed to carbon columns and the metal is almost completely removed from the solution by adsorption on the solid carbon. After the carbon is loaded, it is removed from the circuit and the metal is stripped away. The carbon can also be added to the leaching liquor and agitated without the requirement of carbon columns, known as the "carbon in pulp" process. Desorption or stripping is done by passing a hot, caustic stripping solution over the column. Stripping is followed by electrowinning from solution to produce a very pure gold or silver product. A typical flow sheet, including carbon adsorption, is shown in Fig. 13. The loaded carbon can also be burned, which leaves a gold- or silver-rich ash.

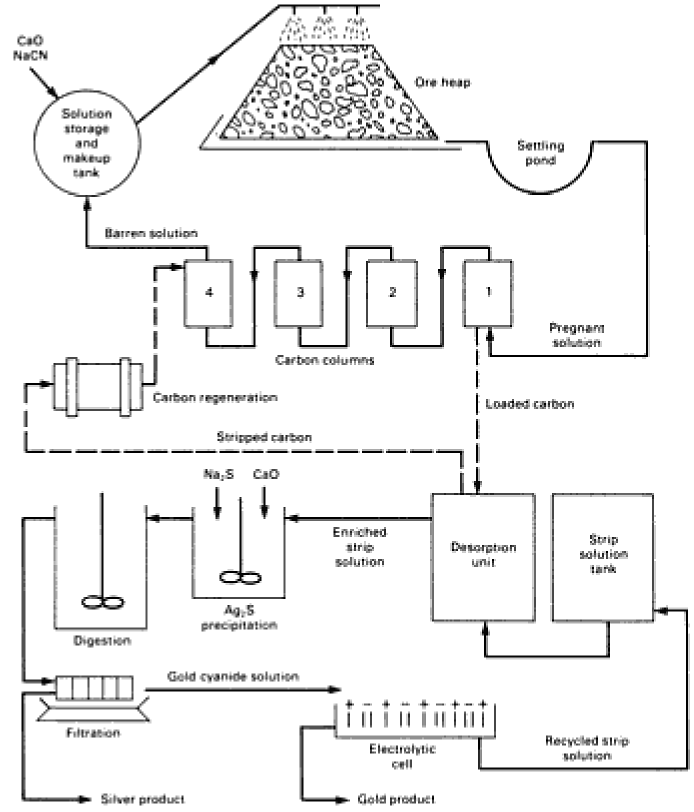
CaO
NaCN
Solution storage and makeup tank
Ore heap
Settling pond
Barren solution
4
3
2
1
Pregnant solution
Carbon columns
Carbon regeneration
Loaded carbon
Stripped carbon
Na_2S
CaO
Enriched strip solution
Desorption unit
Strip solution tank
Ag_2S precipitation
Digestion
Gold cyanide solution
Filtration
Electrolytic cell
Recycled strip solution
Silver product
Gold product

Fig. 13 Heap-leaching charcoal-adsorption process for gold ores low in silver

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Electrometallurgical Processes

Electrometallurgy, or electrolytic processing, deals with the production of metals from ions by application of electrical energy. In contrast with electrochemical processing, where chemical reaction produces electricity as in batteries or corrosion, electrolytic processing uses electricity to perform chemical functions as in metal extraction. Therefore, corrosion is also known as "extractive metallurgy in reverse." As has been discussed thus far, extraction usually implies reduction of a compound, where as corrosion implies oxidation of a metal into a compound. The term electrowinning is used to describe the recovery of metals from a solution or electrolyte on a negative electrode, or cathode, while the positive electrode, or anode, is inert to the ongoing reaction. Electrorefining entails a purification process in which the anode is made of solid impure metal that actively dissolves in the electrolyte; deposition of pure metal occurs on the cathode. These solutions could be generated during leaching and/or purification, as discussed in hydrometallurgy.

Fused salt electrolysis is the production of metals which cannot be electrolyzed from aqueous solution due to their relative positions in the electromotive series and, therefore, are reduced from molten salts. In other words, production of hydrogen from its oxide (water) is, energy-wise, more favorable than the production of metal from its compound. Electrowinning and electrorefining concepts are equally applicable to molten salt electrolysis. If the metal compound has high melting point and is difficult to melt, it may be dissolved in an inert carrier electrolyte (molten salt) which is more stable than the metal compound of interest. The Hall-Héroult process for aluminum production essentially follows this scheme where alumina is dissolved in molten cryolite (sodium-aluminum fluoride).

Basic Concepts

The electromotive series is a listing of the standard half-cell potentials with respect to a reference electrode. The reactions described in establishing an electromotive series are referred to as electrochemical reactions. Electrochemical reactions involve oxidation (loss of electron) and reduction (gain of electron) and can be arranged in an electrochemical (galvanic) cell as shown in Fig. 14. In general, the valence state of the metal is increased in oxidation and decreased in reduction. The oxidation state of a pure metal atom is zero which gets positively ionized by losing electrons. The electrons are picked up by another ionic species, which gets reduced in the solution. If this other ionic species is another metal ion that is reduced on the cathode, the process is known as cementation. It should be memorized that the ions that move towards the anode are anions (negatively charged) and those that are attracted by the cathode are cations (positively charged). The ionic species in the solution (acidic) could be simply protons that can be reduced on the cathode as hydrogen gas.

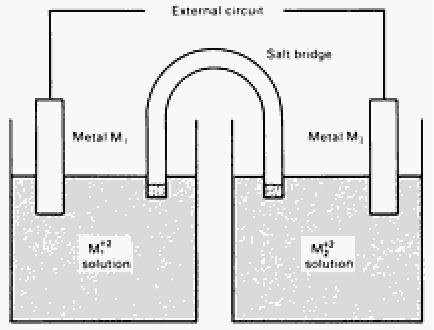

Fig. 14 Electrochemical (galvanic) cell

The potentials on the electromotive series are the minimum theoretical volts required for depositing the metals from a molar solution saturated with its own ions at 25 °C (77 °F), and are measured against a standard reference electrode. For the example of copper metal deposition using zinc metal (Eq 13), an electrochemical cell can be set up, as in Fig. 14, by using a copper electrode as M in a solution of copper sulfate and a zinc electrode as M_2 in a solution of zinc sulfate. If the external circuit is short circuited, electrons will flow from the zinc electrode (anode) to the copper electrode (cathode) as zinc dissolves, which causes deposition of copper metal. By placing a voltmeter between the cathode and the anode, the potential difference between the oxidation and reduction half-reactions can be measured. Because measurement of potential requires measurement between the electrodes, an absolute potential of any half-reaction cannot be measured.

The theoretical dissociation potential required for electrolysis of a compound is given by -c*G*/*nF*, where ΔG is the Gibbs free energy change of the formation of the compound and is a function of temperature and activities of the ions, *n* is the number of electrons transferred in the oxidation-reduction reaction, and *F* is the Faraday Constant (96,486 C). The theoretical current required for metal deposition from the solution is given by Faraday's law, which states that 1 gram-equivalent weight of any metal can be deposited by passing 95,500 ampere-sec of charge (1 faraday). The product of the theoretical potential and current is the theoretical power required. The current and energy efficiencies of an electrolytic cell may be measured as the percent ratios of these theoretical values and the actual amounts of potential applied and current consumed. Efficient electrolytic cells are characterized by high current and energy efficiencies. The theoretical dissociation potential must be exceeded to allow deposition of the metal of interest, but should be kept as low as possible for a higher energy efficiency. Current, in general, is directly linked with the deposition rate, although higher current also implies higher ohmic losses and I^2R heating.

Electrowinning

The electrowinning arrangement usually recycles the acid between the leaching operation and the electrowinning operation for economic efficiency. A simplified diagram of the leaching/electrowinning process is presented in Fig. 15. For example, in the leaching step, the sulfuric acid is consumed as the metal dissolves, according to the reaction in the equation:

$$MO_{(s)} + H_2SO_{4(aq)} \leftrightarrow H_2O + MSO_{4(aq)} \qquad \textbf{(Eq 16)}$$

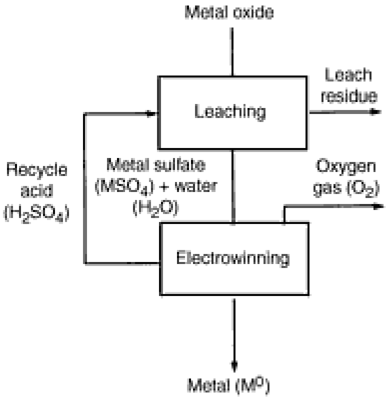

Fig. 15 Simplified block diagram showing the cyclical nature of the leaching/electrowinning process

The leaching solution, $H_2O + MSO_{4(aq)}$, is transferred to the electrowinning step for deposition of the metal. The leaching solution is fed into cells which consist of inert anodes (usually made of lead) and cathodes (which may be made of stainless steel, aluminum, or starter sheets of metal M), arranged as parallel alternating plates of cathodes and anodes. In the electrowinning step, the power supply forces electrons to the cathode, and metal sulfate is reduced to produce the pure metal:

$$MSO_{4(aq)} + 2e^- \leftrightarrow M_{(s)} + SO^{2-}_{4(aq)} \qquad \textbf{(Eq 17)}$$

At the anode, oxygen is produced by decomposition of water and the regeneration of acid is accomplished by the reaction in Eq 19, and recycled back to the leaching step (Eq 16):

$$H_2O \leftrightarrow 2H^+_{(aq)} + \frac{1}{2}O_{(g)} + 2e^- \qquad \textbf{(Eq 18)}$$

$$SO^{2-}_4 + 2H^+ \leftrightarrow H_2SO_4 \qquad \textbf{(Eq 19)}$$

In this case, the potential required between cathode and anode in electrowinning is of the order of 1.25 to 1.75 V. This potential is the combination of the decomposition potential defined earlier (the reversible potential between the cathode and the anode), the ohmic drops or IR losses due to the resistance of the electrolyte, connections and conductors, and polarization of the cell (Ref 23).

The decomposition potential is measured only when the cell reactions take place under conditions of infinitely low current or net zero current. In electrolysis, where current flows at a finite rate, additional voltage drops occur as a result of phenomena that take place near the electrode solution boundaries. These extra voltages are called overvoltages and are caused by reactants not being supplied to electrodes as fast as products are removed (concentration overvoltage) or by molecular phenomena (activation overvoltage) (Ref 23). The resistances of the electrical connections and the electrolyte cause generation of heat as current passes through the cell (Joule heating). The optimum solution temperature in most electrowinning plants is 30 to 45 °C (86 to 113 °F). Temperatures much higher than this can cause deterioration of the cathode deposit as well as increased corrosion of the anodes.

Since the deposited metal must be removed to recycle the cathode, it is important that the metal be loosely bonded to the cathode. For copper electrowinning, titanium, stainless steel, and copper have been used successfully. Aluminum is used to recover zinc and titanium, and stainless steel has been used for electrowinning manganese and cobalt. Electrolytes for electrowinning may also be prepared by externally dissolving the metal in a solvent and pumping it into the cell.

Electrorefining

The advantages of electrorefining over other refinement techniques are the high purity that can be obtained in the product and the recovery of secondary metals (which often are a series of precious metals) in a concentrated state. The secondary metals are recovered from the concentrated form in a separate process. Metals made by smelting of sulfides, such as copper, lead, and nickel, usually are refined by electrolysis. The impurities that contaminate these metals are most often associated with sulfides themselves. The precious metals gold, silver, platinum, and selenium, as well as iron, bismuth, arsenic, and antimony, are usually present. The metal from the smelters, which is from 90 to 98.5% pure, is cast into anodes prior to electrorefining.

The impure anodes are put into cells that contain an acid electrolyte of the anode metal ion. Cathode sheets are placed between the anodes where the pure metal is deposited. A dc power source is wired to the anodes and cathodes in a manner such that electrons are forced into the cathode sheets, causing reduction, and electrons are stripped from the anodes, causing oxidation. At the anode, the oxidation reaction results in the dissolution of the metal by the reaction, $M = M^{2+} + 2e^-$, and the electrons flow back through the power source to the cathode. As the anode dissolves, the impurities either dissolve into the electrolyte with the metal or remain at the anode. The metals that remain in the metallic state are more noble in the electromotive series than the metal that is being refined. As the anode dissolves away, these noble metals fall to the bottom of the cell and collect in a concentrated product that is commonly called "anode slime" or "anode mud." Anode mud is very valuable because it is usually made up of precious metals, such as gold, silver, platinum, and selenium. In copper electrorefining, the slimes can be over 90% silver. The metals that are less noble on the electromotive series of metals dissolve along with the metal that makes up the anode and, if not removed, do build up and contaminate the electrolyte.

Approximately 85% of the anode is allowed to dissolve to retain its mechanical integrity before it is removed from the tank. The unused portion is sent back to the smelter, where it is used as scrap and recast into more anodes. The cycle time for anodes in a typical electrorefining operation is 14 to 28 days. As the electrons are stripped from the anode and forced to the cathode, metal-ion reduction and metal deposition occur on the cathode according to the reaction $M^{2+} + 2e^- = M$.

Because the less noble metals remain in the metallic state as the anode dissolves, the only metal that plates on the cathode is the metal that made up the bulk of the anode. Those impurities that are less noble and get dissolved in the electrolyte are not plated on the cathode and remain in solution as metallic ions. Electrorefined product may also be collected either on another metal sheet or a starter sheet of the metal being plated. The cycle time for cathodes is somewhat longer than the anode cycle time. Current densities on cathodes are kept low to ensure quantity deposits and often are approximately 215 A/m^2 (20 A/ft^2). The physical nature of the deposit is a function of the type of metal ion, current density, deposition temperature, interpolar distance, and deposition rates.

The voltage required between anode and cathode during electrorefining is significantly lower than that required for electrowinning. For example, electrorefining of copper requires only about 0.25 V since the reversible decomposition voltage between two copper electrodes is essentially zero. The other voltage drops, such as the ohmic drops and polarization (overvoltage) exist in electrorefining however.

The cells used for electrorefining are commonly rectangular vats that allow easy placement and removal of anodes and cathodes. The bottoms of the tanks are sloped to allow the collection and flushing of the anode slimes. Since most electrolytes are sulfuric acid base (with the exception of lead electrorefining), the lining material is PVC, rubber, or lead.

Soluble impurities which dissolve with the anode and are not reduced at the cathode must be removed to avoid concentration in the electrolyte. If not removed, these impurities lower the conductivity of the electrolyte, which in turn increases the voltage required and thus increases the energy required. An example of this type of impurity is nickel in copper electrorefining. Nickel is an impurity in the anode that dissolves during electrolysis and collects in the electrolyte. Most copper refiners keep the concentration of nickel below 10 to 20 g/L by continuously bleeding off a small portion of the electrolyte, removing nickel by chemical means, and returning the nickel-free electrolyte to the cells.

Insoluble or more noble impurities that remain in the metallic state collect in the bottom of the electrorefining cells. This anode mud collects until the anode-cathode cycles are complete. At that time, the electrolyte is pumped from the cell, and the slimes are flushed out and collected by filtration. Because the slimes are the final destination of the precious metals, they are further refined to recover gold, silver, platinum, and other associated precious metals.

Molten Salt Electrolysis

As mentioned earlier, reactive metals that are more electropositive in the electromotive series than manganese cannot be electrowon or electrorefined from aqueous solutions because water will decompose at the cathode to form hydrogen gas before reduction of the metal occurs. Therefore, electrolysis of very electropositive metals, such as aluminum, magnesium, lithium, and beryllium, is done from molten salt electrolytes.

Present practice for aluminum electrolysis involves the use of the Hall-Héroult cell as shown in Fig. 16. The cell is lined with carbon, which acts as the cathode; steel bars are embedded in the cathode lining as current collectors. The consumable anodes are also of carbon and are gradually fed into the top of the cell. For aluminum, the electrolyte used is cryolite (Na_3AlF_6) with 8 to 10% Al_2O_3 dissolved in it. Other additives, such as CaF_2 and AlF_3, are added to obtain desirable physical properties, such as fluidity and electrical conductivity. The melting point of the electrolyte is approximately 940 °C (1725 °F), and the Hall-Héroult cell operates at temperatures of approximately 960 to 1000 °C (1760 to 1830 °F) with a power rating of 10 to 12 kWh/kg aluminum.

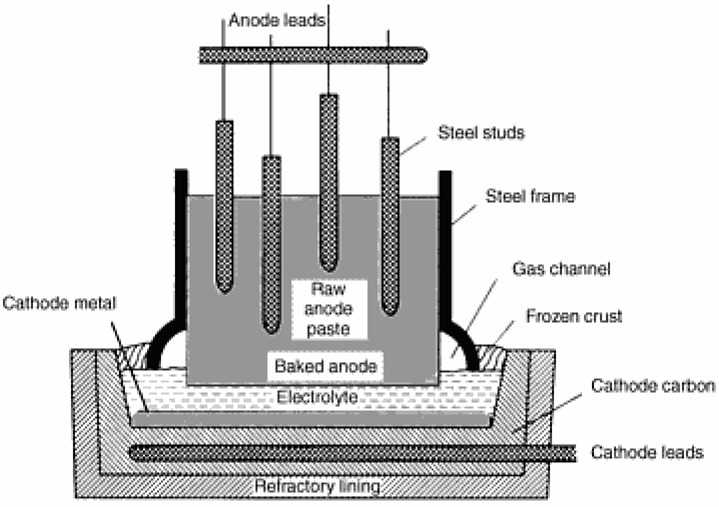

Fig. 16 Hall-Héroult aluminum production cell with self-baking anode. Source: Ref 5

Electrochemically, aluminum is reduced at the cathode from an ionic state to a metallic state by:

$$Al^{3+} + 3e^- \leftrightarrow Al_{(l)} \qquad \textbf{(Eq 20)}$$

This simplified reaction goes through a series of complex reactions that take place at the cathode (Ref 26). It does represent the overall production of molten aluminum, which forms a molten pool in the bottom of the cell. Periodically, the molten pool of aluminum metal is drained or siphoned from the bottom of the cell and cast.

At the anode, oxygen is oxidized from its ionic state to oxygen gas which, in turn, reacts with the carbon anode to form carbon dioxide gas, gradually consuming the anode material. Two types of anodes are in use: prebaked and self-baking. Prebaked anodes are individual carbon blocks that are replaced one after another as they are consumed. Self-baking anodes, as shown in Fig. 16, are made up of a carbon paste that is fed into a steel frame above the cell. As the anode descends in the cell it hardens, and new carbon paste is fed continually into the top of the steel frame.

Impurities in the aluminum oxide raw material that are more noble than aluminum, such as iron and silicon, are reduced at the cathode along with the aluminum. It is, therefore, important that raw materials be prepared in the Bayer's process as free of these metal oxides as possible. By careful control of raw materials, aluminum with a purity of over 99% can be produced.

Magnesium is produced by molten salt electrolysis. Magnesium does not alloy with iron, and so the cells consist of iron pots as cathodes and carbon anodes. The electrolyte used is a magnesium chloride-sodium chloride-calcium chloride mixture that allows the process to be run at approximately 750 °C (1382 °F). The raw material for magnesium may be either magnesium chloride or magnesium oxide. Magnesium electrolysis differs from aluminum electrolysis in that the magnesium metal formed at the cathode is less dense than the electrolyte and rises to float on top of the electrolyte; this requires special precautions when the molten metal is recovered from the cell. Production of calcium by molten salt electrolysis has been developed successfully from molten calcium oxide-calcium chloride salt mixtures using carbon anodes. Presently, a great deal of research effort is concentrated on eliminating the consumable carbon anode from these fused salt electrolytic processes. Inert ceramic anodes that conduct oxygen ions and are based on spinel and perovskite compositions have been developed. Carbon electrodes impregnated with titanium diboride have been successfully used in the industry.

The science of extractive metallurgy has more or less remained the same over several decades (Ref 27). However, significant progress has been made in the technology and application of this science to extract metals cheaply, efficiently, and in an environment-friendly manner.

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General Introduction to Casting

Thomas S. Piwonka, The University of Alabama

Introduction

METAL CASTING is the manufacturing method in which a metal or an alloy is melted, poured into a mold, and allowed to solidify. It is one of the oldest manufacturing methods known to humankind, and one of the most versatile. Today's foundries make use of statistical process control and sophisticated solidification simulation software, and castings today are highly reliable, cost-effective components that are utilized in more than 90% of manufactured products. Typical uses of castings include municipal hardware, water distribution systems (pipes, pumps, and valves), automotive components (engine blocks, brakes, steering and suspension components, etc.), prosthetics, and gas turbine engine hardware.

Casting Flow Chart

The steps in making a casting are shown in Fig. 1. Before the casting can be made, the alloy must be melted, and the mold must be made. The mold is usually made of a material with a higher melting point than that of the alloy, such as a refractory aggregate (e.g., silica sand) or a high-temperature alloy. There are a wide variety of mold-making methods used in casting, depending on the alloy to be poured, the number of castings to be made, the dimensional requirements of the casting, and the property requirements of the casting. Figure 1 depicts the sand molding process, the most commonly used molding (casting) method. A more detailed account of this process can be found in the article "Molding Methods" in this Section.

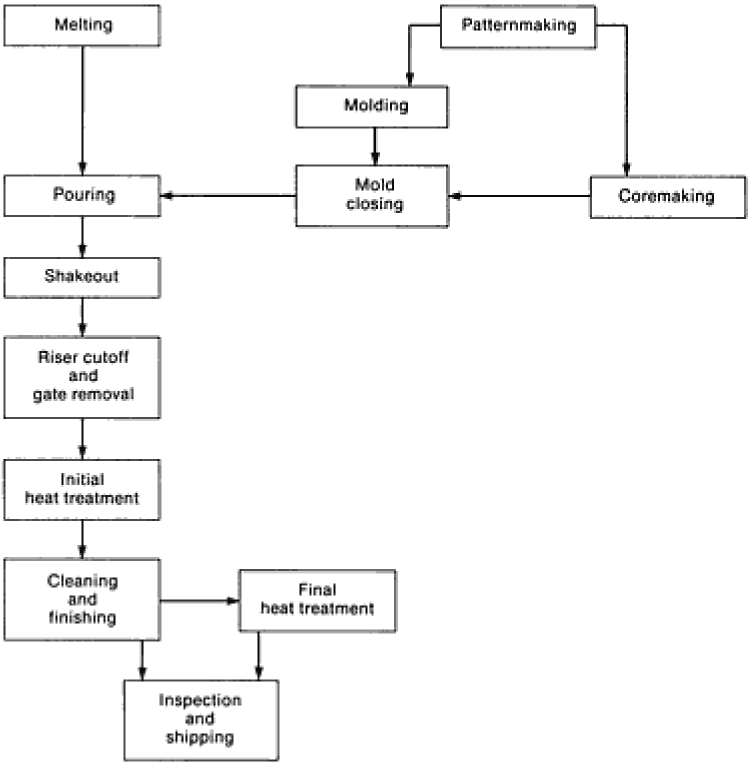

Fig. 1 Simplified flow diagram of the basic operations for producing a steel casting. Similar diagrams can be applied to other ferrous and nonferrous alloys produced by sand molding

The right side of Fig. 1 begins with the task of patternmaking. A pattern is a specially made model of the component to be produced, used for producing molds. Generally, sand is placed around the pattern, and, in the case of clay-bonded sand, rammed to the desired hardness. In the case of chemical binders, the mold is chemically hardened after light manual or machine compaction. Molds are usually produced in two halves so that the pattern can be easily removed. When these two halves are reassembled, a cavity remains inside the mold in the shape of the pattern.

Internal passageways within a casting are formed by the use of cores. Cores are parts made of sand and binder that are sufficiently hard and strong to be inserted into a mold. Thus, the cores shape the interior of the casting, which cannot be shaped by the pattern itself. The patternmaker supplies core boxes for the production of precisely dimensioned cores. These core boxes are filled with specially bonded core sand and compacted much like the mold itself. Cores are placed in the drag, or bottom section, of the mold, and the mold is then closed by placing the cope, or top section, over the drag. Mold closing completes the production of the mold, into which the molten metal is then poured.

Casting production begins with melting of the metal (left side of Fig. 1). Molten metal is then tapped from the melting furnace (see the article "Melting Methods") into a ladle for pouring into the mold cavity, where it is allowed to solidify within the space defined by the sand mold and cores. After it has solidified, the casting is shaken out of the mold, and the risers and gates are removed. Risers (also called "feeders") are shapes that are attached to the casting to provide a liquid-metal reservoir and control solidification. Metal in the risers is needed to compensate for shrinkage that occurs during cooling and solidification. Gates are the channels through which liquid metal flows into the mold cavity proper. Cleaning and finishing, heat treatment, and inspection follow. The article "Solidification of Metals and Alloys" provides a more detailed account of how castings solidify in the mold, shrinkage characteristics, as well as gating and risering practices.

Casting Alloys

Alloys used for metal casting may have the same composition as alloys used in other forming methods. However, many of the alloys used in casting have been developed expressly for the casting process, and these alloys do not have analogs for other forming processes. They exist only in the cast form, as their performance depends on the unique metallurgical structure produced during solidification. In addition, many of the alloys that exist in cast and wrought form often have slight variations in chemistry to facilitate the casting process. It is important to know exactly which composition is meant when dealing with these alloys.

Ferrous alloys include both cast irons and steels. Cast irons generally refer to iron alloys containing 3 to 4% carbon, with silicon contents of 1.5 to 2.5%. Cast irons, which are melted in induction furnaces, cupolas, and electric arc furnaces, are generally poured/cast into sand molds. Steels include all alloys containing less than 2% carbon, with additions of small amounts of manganese and silicon, and other alloying elements as needed. Most steel is arc melted and poured into sand molds.

Nonferrous castings are used where ferrous castings would be too heavy, too expensive, or lack the properties required for the application. These alloys are generally melted in crucible furnaces, reverberatory furnaces, or induction furnaces. Molding techniques are similar to those used for ferrous alloys, but, because most nonferrous alloys melt and solidify at lower temperatures than ferrous alloys, metal molds are frequently used.

Solidification of Metals and Alloys

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Introduction

SOLIDIFICATION is the transformation of liquid to solid. During this process, atoms change their arrangement from randomized short-range order to regular positions on a crystallographic lattice. In doing so, they give up energy in the form of heat, which must be removed by the mold. The energy they give up is called the "latent heat of fusion."

Pure Metals

Pure metals give up their latent heat of fusion and solidify at a single temperature. If a pure metal is melted and allowed to solidify in the melting crucible, a thermocouple placed in the metal during solidification will show the trace shown in Fig. 1. The temperature will fall until the melting point is reached (it will actually fall a little below the melting point and then recover as solidification begins). At the melting point, the temperature will remain constant until all of the metal has completed its transformation and given up its latent heat of fusion. The temperature will then continue to fall to room temperature.

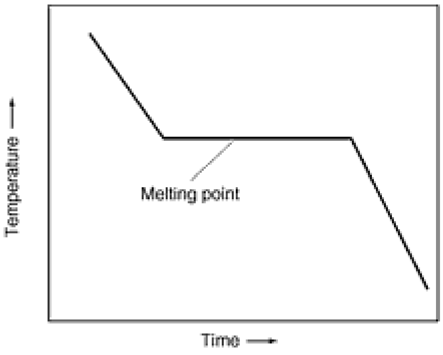


Fig. 1 Thermocouple trace for a pure metal solidifying in a mold

Solidification begins with a nucleation event. Although it is possible under very closely controlled conditions to cool the metal far below its melting point ("undercooling"), in practice the undercooling experienced is very small. This is because commercial melts always contain some sort of nucleating agent. Most often this agent will be the wall of the mold itself.

However, other agents may be deliberately added to the melt to control the nucleation event and the degree of undercooling. For example, this is especially important in controlling the solidification of cast iron.

Because the mold is cooler than the metal, nucleation will occur all over the surface of the mold. Each nucleation event will produce an individual crystal, or grain, which then will attempt to grow. These randomly oriented grains form a "chill zone" next to the mold wall. The grains are oriented randomly with respect to the mold; that is, the major axis of each grain is randomly oriented. As each metal grows most favorably in one principal crystallographic direction, only those grains favorably oriented with their growth direction most perpendicular to the mold wall will grow into the center of the casting (Fig. 2). The grains in a pure metal will grow until they impinge on another grain.

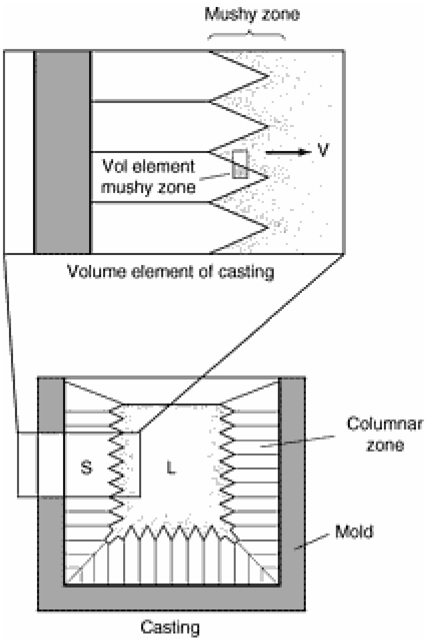


Fig. 2 Solidification in conventional castings. During the growth of the columnar zone, three regions can be distinguished. These are the liquid (L), the liquid plus solid (the so-called "mushy" zone), and the solid (S) regions.

The fact that the grains most favorably oriented to the mold wall grow the fastest means that the final shape of the grains in a pure metal casting is columnar. As shown in Fig. 2, the grains form parallel columns, growing progressively from the mold wall into the center of the casting.

The density of the solid phase is different than that of the liquid phase. In almost every metal, the solid is more dense than the liquid. The solid will occupy less space than the liquid; in other words, it will shrink in volume. Because this shrinkage occurs at the point of solidification, the volume deficit, which is called the shrinkage cavity, is found at the location of the last liquid to solidify. Figure 3 shows the formation of a shrinkage cavity in a pure metal solidifying in a mold where all heat is removed through the mold. If the final casting is to have the same volume as the liquid, a reservoir of molten metal must be placed on the casting to feed liquid metal to the mold cavity. This extra metal is called the feeder, or the riser.

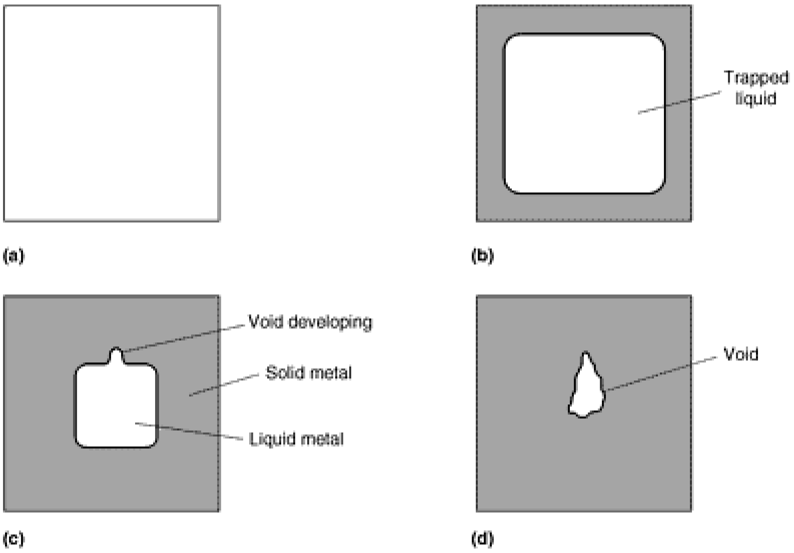

(a)
(b)
Trapped liquid
Void developing
Solid metal
Liquid metal
(c)
Void
(d)

Fig. 3 Development of shrinkage void in a casting. (a) Liquid. (b) Liquid + solid. (c) Liquid + solid. (d) Solid

Alloys

The solidification of alloys is more complex. Alloys are solutions of one or more metals or semimetals in another metal. As such, they solidify over a range of temperatures. The temperature range over which solidification takes place under equilibrium conditions is found from the phase diagram. The temperature at which solidification begins is called the liquidus temperature, and the temperature at which it ends in equilibrium solidification is called the solidus. This range is often referred to as the "mushy zone," because the material in this temperature range is a mixture of liquid and solid (Fig. 2). Figure 4 shows a simplified phase diagram for a binary alloy system. Note that almost all commercial alloys have three or more components; as such, their solidification is more complex than for binary alloys.

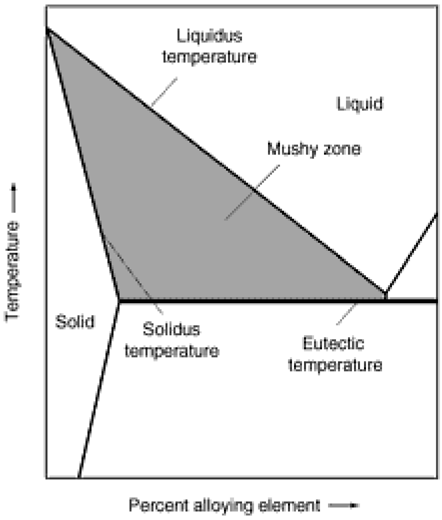

Liquidus temperature
Liquid
Mushy zone
Temperature ⟶
Solid
Solidus temperature
Eutectic temperature
Percent alloying element ⟶

Fig. 4 Simplified phase diagram, showing positions of liquidus, solidus, and eutectic temperatures, and the mushy zone

Dendrite Formation. During alloy solidification, instabilities in the solid at the liquid/solid interface grow, leading to the formation of dendrites (Fig. 5). Dendrites have a primary arm, secondary arms that branch from it, and tertiary arms that branch from the primary arm. The spacing of the secondary arms is proportional to the rate at which heat is removed from the casting during solidification. Each crystal consists of a single dendrite.

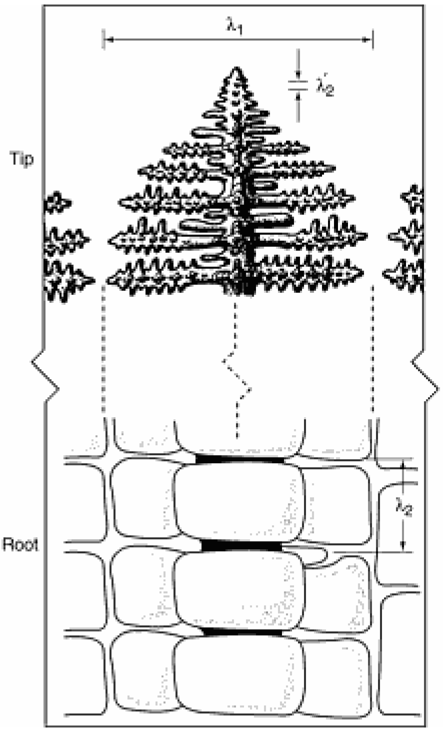


Fig. 5 Growing dendrite tip and dendrite root during columnar growth in a casting. A dendritic form is usually characterized in terms of the primary (dendrite trunk) spacing, λ_1, and the secondary (dendrite arm) spacing, λ_2.

Segregation. During equilibrium alloy solidification, solute atoms are rejected into the liquid, according to the lever rule. Thus, the composition of the unsolidified liquid changes during solidification, and the last liquid to solidify has a different composition than that of the first liquid to solidify. The change in composition is referred to as segregation. When large areas of the casting show differences in composition from the nominal composition of the alloy that was poured to make the casting, macrosegregation results. However, segregation also occurs between the dendrite arms, where solidification is taking place.

Segregation has a number of effects. During solidification it causes the composition to change locally over the casting (Fig. 6). This local change in composition may result in the formation of different phases or compounds, such as carbides or intermetallic phases, which would not otherwise be stable at the nominal composition of the alloy. These local phases may degrade casting properties. Because the rejection of solute into the liquid changes not only the composition of the liquid but also its density, convection currents caused solely by segregation (solutal convection) may be set up in the casting. The amount of shrinkage that occurs locally will also be a function of the local composition of the liquid when it solidifies. A major effect of segregation is that heat treatment times may be lengthened; the time to homogenize a casting will depend on the dendrite arm spacing (the distance over which solute atoms must travel to go into solution) and the amount of segregation. Because segregation causes the casting composition to vary locally, chemical etching can reveal the cast structure, which makes metallography possible.

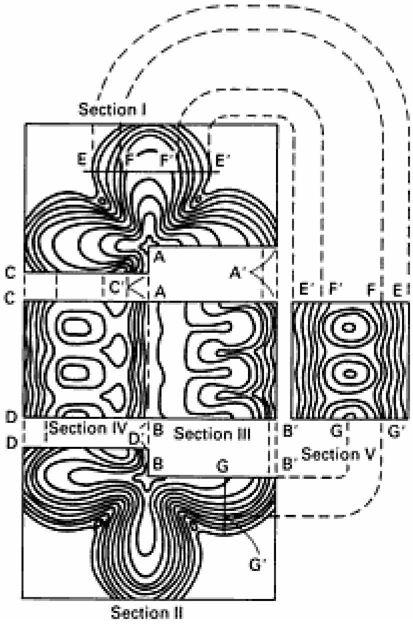


Fig. 6 Isoconcentration profile lines in an Fe-25Cr-20Ni columnar dendrite showing that the chemical concentration of elements is not constant within the dendrite.

When metal is poured into a mold, the liquid has a velocity from the pouring operation. In addition, as the metal cools at the mold wall, thermal convection currents are set up at the mold wall, with the cooling metal traveling downward along the mold wall. These currents, combined with solutal convection and the residual liquid motion from pouring mean that the liquid in the unsolidified part of the casting is in motion. This movement is usually beneficial, as the motion minimizes macrosegregation in small castings (although it magnifies it in large castings).

Alloys nucleate in the same manner as pure metals. However, during solidification, the liquid motion may break off dendrites and carry them into the liquid. Then the dendrites act as nuclei for more grains and multiply the number of grains that nucleate in the liquid. In addition, solute rejection (segregation) may form a region of liquid where the melting point of the liquid rises above the temperature of the melt, meaning that the liquid in that region is now below its melting point. Even though the actual temperature of the liquid has not changed, the change in composition resulting from segregation yields an alloy composition locally that has a melting temperature above that of the liquid. This is called constitutional supercooling. The result of these two mechanisms refines the final grain structure of the casting.

Structural Zone Formation. Solidification begins, as in pure metals, with nucleation of solid on the walls of the mold, again forming a chill zone. Then those grains that are most favorably oriented grow inward, forming a columnar zone. However, because of segregation, there is constitutional supercooling and grain multiplication. As a result, the last liquid to solidify does so as equiaxed grains. Thus, the final structure of the casting has three zones (Fig. 7). In the equiaxed zone, the grains do not grow progressively from the solid that has already solidified. Instead, they grow simultaneously from their own nuclei, until they impinge on neighboring grains.

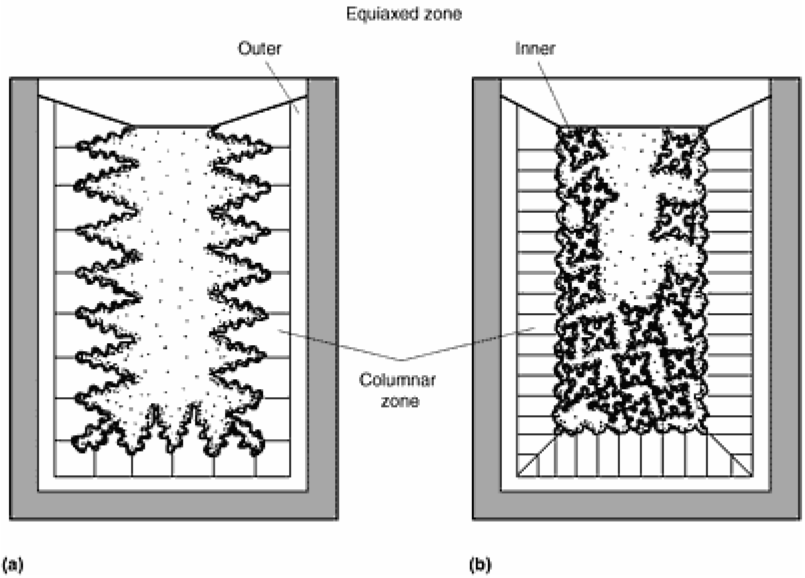


Fig. 7 Three structural zones forming in a casting. (a) Early in the solidification process, solid nuclei appear at, or close to, the mold wall. For a short time, they increase in size and form the *outer equiaxed zone*. Then, those crystals (dendrites) that can grow parallel and opposite to the heat flow direction will advance most rapidly. Other orientations tend to be overgrown, due to mutual competition, leading to the formation of a *columnar zone*. (b) Beyond a certain stage in the development of the columnar dendrites, branches that become detached from the latter can grow independently. These tend to take up an equiaxed shape because their latent heat is extracted rapidly through the undercooled melt. The solidified region containing them is called the *inner equiaxed zone*.

The amount of the final cast structure that is columnar or equiaxed depends on the alloy composition and on the thermal gradient at the liquid/solid interface during solidification. The thermal gradient is most easily controlled by controlling the rate of heat extraction from the casting, or the cooling rate. Alloys that have a wide spread between the liquidus and the solidus temperature solidify with a mostly equiaxed grain structure at normal cooling rates, whereas alloys with small differences in solidus and liquidus temperatures solidify with a mostly columnar structure. High cooling rates encourage columnar solidification because they establish high thermal gradients at the liquid/solid interface. Low thermal gradients encourage equiaxed solidification.

Shrinkage. Like pure metals, alloys shrink as they solidify. However, feeding the shrinkage in the equiaxed zone is far more difficult than feeding shrinkage in the columnar zone. In the equiaxed zone, the liquid must wind its way down tortuous interdendritic channels to feed the shrinkage occurring at the end of these channels. As these channels narrow, feeding becomes finally so difficult that the metal is unable to reach the areas where solidification is occurring. As a result, tiny micropores form between the equiaxed grains. This condition is known as microporosity.

Effects of Nonequilibrium Conditions. The discussion to this point has assumed that solidification takes place under equilibrium conditions. However, in actual castings, this is not true. Equilibrium solidification occurs at rates so slow that there is perfect diffusion in the liquid and in the solid, so that the composition of the alloy shown on the phase diagram is what is found everywhere in the casting. However, real castings solidify much more quickly than the equilibrium rate, and many castings solidify at high rates. The faster the solidification rate is, the greater the departure from equilibrium will be. Departures from equilibrium exaggerate segregation. They also depress the liquidus and solidus temperatures. Indeed, it is common for the last metal to solidify as a eutectic because of departures from equilibrium during solidification. It is important to remember in analyzing castings that there is this departure from equilibrium caused by solidification rate. Because solidification rate varies with location in the casting (it is higher at the edges and corners of the casting, and lower in the interior of heavy sections), the departure from equilibrium varies with location in the casting.

Eutectic Phases

When the liquid has the composition of the eutectic, it solidifies forming two distinct phases in intimate contact with each other (Fig. 8). Eutectic, or near-eutectic, alloys are common in casting. In fact, one of the most common casting alloys, cast iron, gets its distinctive microstructure from the controlled solidification of the eutectic phase.

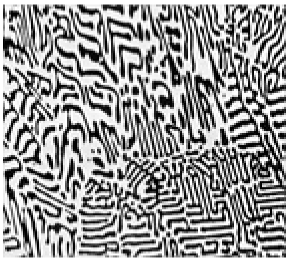


Fig. 8 Irregular "Chinese script" eutectic consisting of faceted Mg_2Sn phase (dark) in a magnesium matrix. Etched with glycol. 250×

Eutectics have the lowest melting point in the alloy and high fluidity. Near-eutectic alloys flow easily into the mold. When the temperature falls below the eutectic temperature, the casting is solid. A more detailed account of eutectic phases can be found in the Section "Structure and Properties of Metals" in this Handbook.

Imperfections

During solidification, atoms leave the liquid and arrange themselves as a solid. During this process, many things can happen to cause imperfections (defects) in the solid.

Porosity is the presence of pores in the casting. These pores may be connected to the surface, where they can be detected by dye penetrant techniques, or they may be wholly internal, where they require radiographic techniques to be discovered. Macroporosity refers to pores that are large enough to see with the unaided eye on radiographic inspection, while microporosity refers to pores that are not visible without magnification.

Both macroporosity and microporosity are caused by the combined action of metal shrinkage and gas evolution during solidification. It has been shown that nucleation of pores is difficult in the absence of some sort of substrate, such as a nonmetallic inclusion, a grain refiner, or a second-phase particle. Numerous investigations have shown that clean castings, those castings free from inclusions, have fewer pores than castings that contain inclusions. Microporosity is found not only in castings but also in heavy section forgings, which have not been worked sufficiently to close it up.

When the shrinkage and the gas combine to form macroporosity, properties are deleteriously affected. Static properties are reduced at least by the portion of the cross-sectional area taken up with the pores. Because there is no metal in the pores, there is no metal to support the load there, and the section acts as though its area was reduced. Because the pores may also cause a stress concentration in the remaining material, static properties may be reduced by more than the percentage of cross-sectional area caused by the macroporosity.

Dynamic properties are also affected. A study of aluminum alloys showed that fatigue properties in some alloys were reduced 11% when specimens having x-ray quality equivalent to ASTM E 155 level 4 were tested, and that they were reduced 17% when specimens having quality of ASTM E 155 level 8 were tested.

Static properties are mostly unaffected by microporosity. Microporosity is found between dendrites, and, like macroporosity, it is caused by the inability of feed metal to reach the interdendritic areas of the casting where shrinkage is occurring and where gas is being evolved. However, because this type of porosity occurs late in solidification, particularly in long range freezing ("mushy freezing") alloys, it is particularly difficult to eliminate. The most effective method is to increase the thermal gradient (often accomplished by increasing the solidification rate), which decreases the length of the mushy zone. This technique may be limited by alloy and mold thermal properties, and by casting geometry (i.e., the design of the casting).

As long as the micropores are less than 0.2 mm in length, there is no effect on dynamic properties: fatigue properties of castings with pores that size or smaller are in the same range as those of castings where no micropores were found. The shape of the micropore is as important as its size, with elongated pores having a greater effect than round pores. Areas where microporosity is expected can be predicted by solidification modeling, similar to the prediction of macroporosity (see below). Microporosity can be healed by hot isostatic pressing (HIP). In one study comparing HIP and non-HIP samples, no difference was found in fatigue lives. However, the HIP samples showed a lower crack growth rate than non-HIP samples. In another study, HIP improved fatigue crack growth resistance only close to threshold levels. As noted above, the design of the casting directly affects its tendency to solidify in a progressive manner, thereby affecting both the quality and the price of the cast component.

Porosity and casting costs are minimized in casting designs that emphasize progressive solidification toward a gate or riser, tapered walls, and the avoidance of hot spots.

Inclusions are nonmetallic particles found in the casting. They may form during solidification, as some elements (notably manganese and sulfur in steel) precipitate from solution in the liquid during solidification. More frequently, they form before solidification begins. The former are sometimes called "indigenous" inclusions, and the latter are called "exogenous" inclusions. Inclusions are ceramic phases: they have little ductility. A crack may form in the inclusion and propagate from the inclusion into the metal, or a crack may form at the interface between the metal and the inclusion. In addition, because the inclusion and the metal have different coefficients of thermal expansion, thermally induced stresses may appear in the metal surrounding the inclusion during solidification. As a result, the inclusion acts as a stress concentration point and reduces dynamic properties. As in the case of microporosity, the size of the inclusion and its location determine its effect. Small inclusions that are located well within the center of the cross section of the casting have little effect, whereas larger inclusions and those located near the surface of the casting may be particularly detrimental to properties. Inclusions may also be a problem when machining surfaces, causing excessive tool wear and tool breakage.

Exogenous inclusions are mostly oxides or mixtures of oxides and are primarily slag or dross particles, which are the oxides that result when the metal reacts with oxygen in the air during melting. These inclusions are removed from the melt before pouring by filtration. Most inclusions found in steel castings arise from the oxidation of metal during the pouring operation. This is known as reoxidation, and takes place when the turbulent flow of the metal in the gating system causes the metal to break up into small droplets, which then react with the oxygen in the air in the gating system or casting cavity to form oxides. Metalcasters use computer analysis of gating systems to indicate when reoxidation can be expected in a gating system and to eliminate them. However, casting designs that require molten metal to jet through a section of the casting to fill other sections will recreate these inclusions and should be avoided.

Oxide films are similar to inclusions and have also been found to reduce casting properties. Oxide films form on the surface of the molten metal as it fills the mold. If this surface film is trapped within the casting instead of being carried into a riser, it is a linear discontinuity and an obvious site for crack initiation. It has been shown that elimination of oxide films, in addition to substantially improving static properties, results in a five-fold improvement of fatigue life in axial-tension tension tests.

Oxide films are particularly of concern in nonferrous castings, although they also must be controlled in steel and stainless steel castings. Because of the high carbon content of cast iron, oxide films do not form on that particular metal. If the film is folded over on itself as a result of turbulent flow or "waterfalling" (when molten metal falls to a lower level in the casting during mold filling), the effects are particularly damaging. Casting design influences how the metal fills the mold, and features of the design that require the metal to fall from one level to another while the mold is filling should be avoided so that waterfalls are eliminated. Oxide films are avoided by filling the casting from the bottom in a controlled manner, by pumping the metal into the mold using pneumatic or electromagnetic pumps.

Secondary phases that form during solidification may also nucleate cracks if they have the proper size and morphology. An example is aluminum-silicon alloys, where the silicon is present in the eutectic phase as large platelets, which nucleate cracks, and along which cracks propagate. The size of these platelets may be significantly reduced by modifying the alloy with additions of sodium or strontium. However, such additions increase the size of micropores, and for this reason many foundrymen rely on accelerated solidification of the casting to refine the silicon. As previously noted, solidification rates normally increase and the structure is thus refined in thin sections. Heavy sections are to be avoided if a fine structure is desired. Generally speaking, however, secondary phases in the structure of castings become important in limiting mechanical behavior of castings only in the absence of nonmetallic inclusions and microporosity.

Hot tears form when casting sections are constrained by the mold from shrinking as they cool near the end of solidification. These discontinuities are fairly large and most often weld-repaired. If not repaired, their effect is not readily predictable; while generally they are detrimental to casting properties, under some circumstances they do not affect them. Hot tears are caused by a combination of factors, including alloy type, metal cleanliness, and mold and core hardness. However, poor casting design is the primary cause. Castings should be designed so that solidifying sections are not subjected to tensile forces caused by shrinkage during solidification, as the solidifying alloy has little strength before it solidifies.

Metal Penetration. Molten metal may penetrate the surface of the mold forming a rough surface, or in extreme cases, it may actually become intimately mixed with the sand in the mold. In iron castings, this is normally the result of the combination of metallostatic head (the pressure exerted on the molten iron at the bottom of the mold by the weight of the metal on top of it) and the surface tension relationships between the liquid iron and molding materials. In cast iron, it is frequently also the result of the expansion of graphite at the end of solidification forcing liquid metal into the mold. This penetration can occur if the casting is not properly designed with a tapered wall to promote directional solidification and avoid hot spots. In steel castings, penetration may also occur as a result of formation of iron or manganese oxide on the surface of the molten metal. These oxide phases react with the silica sand to form chemical penetration, which is difficult to remove from the surface of the casting. Use of mold coatings can protect the mold from this reaction.

Gating and Risering

To make a casting, the metalcaster must fill the mold with metal and then control the solidification of the casting to prevent the formation of casting imperfections. The techniques used to accomplish this are called gating and risering, or rigging.

Gating

Gating System Components. The gating system is the plumbing system that fills the mold with molten metal. Gating system nomenclature is shown in Fig. 9. Metal is poured into the pouring basin, down a sprue, where it enters the runner, which delivers it to gates, through which it flows into the casting cavity in the mold. Filters placed in the runners slow the metal and remove inclusions, and vents on the casting allow air to escape and relieve the back pressure that opposes mold filling.

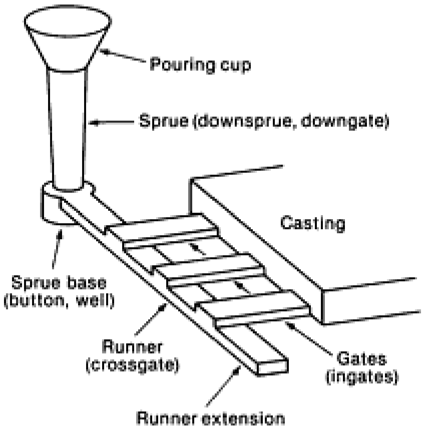


Fig. 9 Basic components of a simple gating system for a horizontally parted mold

Recommended Practices. The gating system must fill the mold quickly, while minimizing turbulence. Turbulence causes the molten metal to mix with the air in the sprue and runners. The oxygen in the air reacts with the molten metal, forming oxide inclusions. Unfortunately, it is difficult to minimize turbulence in gating systems in medium-size and large castings, as the velocity the metal reaches on falling down the sprue is usually so great that turbulence is unavoidable. Ceramic filters slow the velocity of the metal in the runner, which fills the sprue with metal. Good gating practice recommends that the system be unpressurized, that is, the cross-sectional area of the down sprue should be less than the total cross-sectional area of the runners, which, in turn, should be less than the total cross-sectional area of the gates.

Runner cross sections are usually rectangular, so that metal does not swirl down the runners and entrap air. Runners should be free from sharp edges, and gates should be filleted.

The gating system should establish thermal gradients to promote a sound (porosity-free) casting. The ideal situation is to have the casting freeze from thin sections (which freeze quickly) to thick sections, so that feed metal is available to feed shrinkage as it occurs. As molten metal flows through the gating system, it loses heat to the runners and heats them up. Thus, the first metal into the mold is coldest, and the last metal is hottest. For this reason, gates should be placed into heavy sections of the casting, so that hot metal is available to feed shrinkage that occurs in the casting as the casting solidifies. By having solidification take place progressively toward the gates and risers, shrinkage is avoided.

Good gating systems should avoid reoxidation of the metal, avoid the formation of oxide folds, and, if possible, remove oxide and dross from the molten metal. Gating systems should be designed to prevent the aspiration of air through the porous molding media. The position of the casting in the mold should be given careful thought. Normally the casting should have its longest dimension parallel to the parting plane. Metal should not drop from one level in the casting cavity to a lower level because the oxide film that forms on the top of the molten metal mixes into the metal in the casting, which causes inclusions.

Filters strain out most of the slag or dross that may have been carried in from the melting operation, and pieces of mold refractory that may have come loose during molding. Metal should not rain down from the top of the sprue or into the casting because it will react with the air in the runner system or the casting cavity. Therefore, filters should not be placed at the top of the sprue, and gates should be placed at the bottom of the mold, so that the casting cavity fills from the bottom. The proper placement of filters in gating systems is shown in Fig. 10. Filters are used in all alloys except titanium.

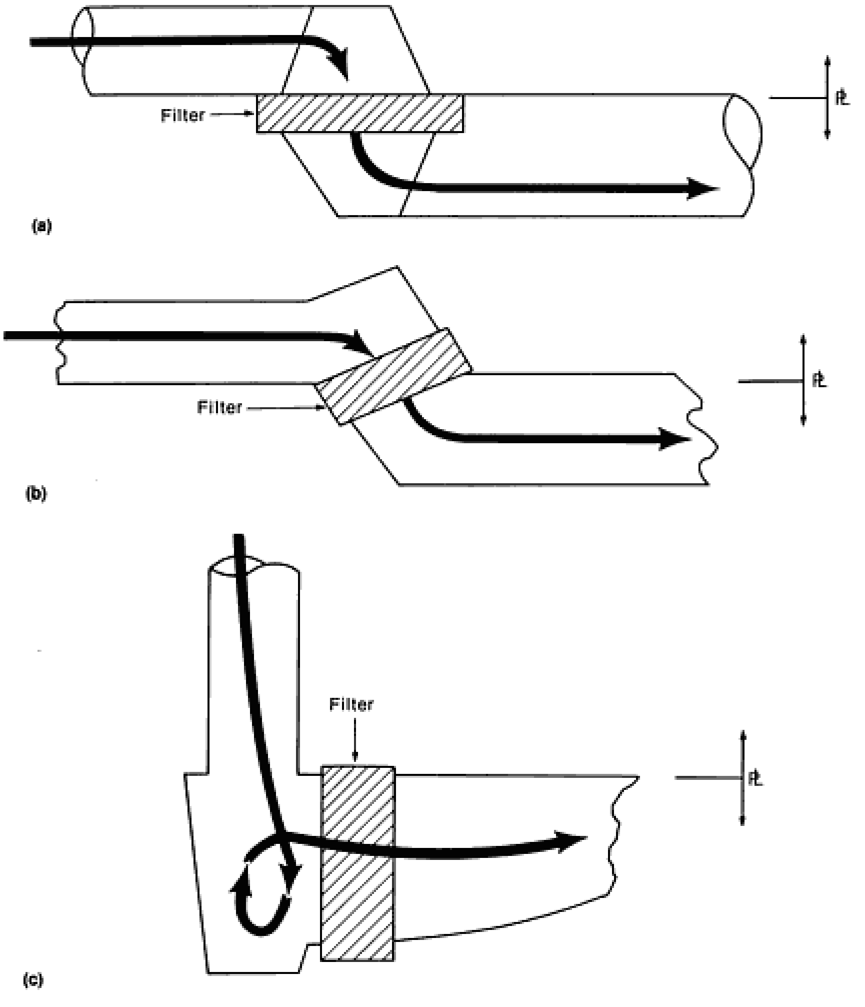


Fig. 10 Common methods of filter placement in horizontally parted molds. (a) Parallel to parting line. (b)

Between 0 and 90° to parting line. (c) 90° to parting line. Arrows indicate the direction of metal flow.

Pouring metal down a sprue causes the metal to accelerate due to gravity. The increased velocity caused by this acceleration leads to turbulent flow and the formation of inclusions. One method of avoiding turbulent flow is to use some form of counter-gravity mold filling, as shown in Fig. 11. Counter-gravity pouring systems allow the rate of fill to be controlled precisely; it can be speeded up or slowed down as necessary to compensate for changes in the cross-sectional area of the casting. In filling the mold from the bottom, the rate of rise in the casting cavity should be no greater than 0.5 m/s (1.65 ft/s) for aluminum alloys and no greater than 0.3 m/s (1 ft/s) for copper-base alloys. Filters are incorporated in the fill tubes used in counter-gravity gating systems. Counter-gravity pouring systems operate at the same speed as conventional pouring lines; a number of techniques, such as rotating the mold around a horizontal axis at the bottom of the mold after pouring, are available to prevent molten metal from draining out of the casting cavity until solidification is complete.

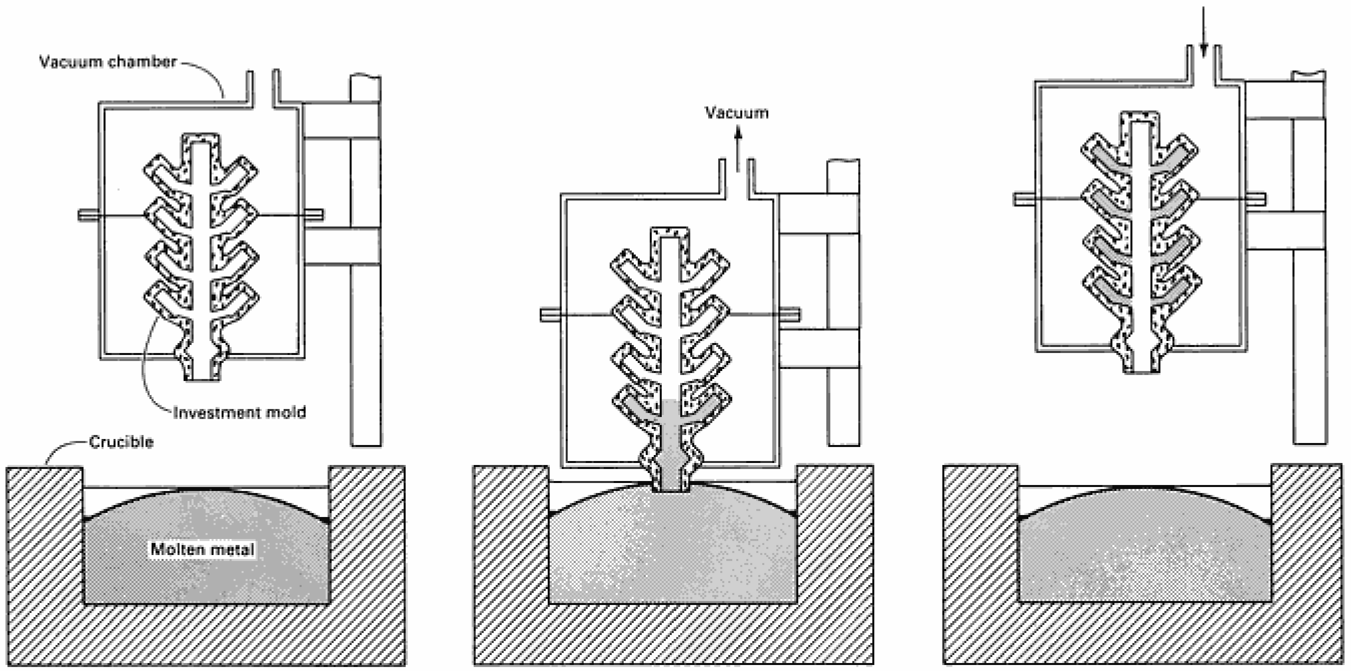


Fig. 11 Schematic of the operations of the counter-gravity low-pressure casting process. (a) Investment shell mold in the casting chamber. (b) Mold lowered to filling position. (c) Mold containing solidified castings; most of the gating has flowed back into the melt.

Gates must be easy to remove, and they must not distort the casting when they solidify. If they are to be cut off or sawed off, room must be available for the cutting torch or saw blade. When more than one gate is used to fill a casting, care should be taken that the solidification of the runner that connects the gates does not distort the casting when the runner, which must stay liquid long enough to fill the casting, freezes and contracts due to shrinkage.

Gating design calculations may be done approximately by using Bernoulli's theorem, which is an energy and materials balance between points in the gating system. More accurate gating designs may be made using a combination of expert systems and finite element or finite difference solutions of fluid flow equations. These are part of commercial solidification software widely available to metalcasters.

In a mold having more than one mold cavity of the same casting geometry, it is recommended that the gating of all of the castings be identical. This match assures that all castings solidify similarly. Differences in solidification sequence otherwise may cause castings to have properties that vary according to their position in the mold.

Good pouring practice means filling the sprue rapidly and keeping it full while the casting cavity fills. There are essentially three types of pouring ladles for gravity pouring (Fig. 12). Keep in mind that slag and dross will form on the top of the metal in the ladle where the molten alloy is exposed to the atmosphere. With the open lip ladle (Fig. 12a), the slag or dross must be held back during pouring. The teapot ladle (Fig. 12b) is most effective for keeping slag out of the mold. Bottom pour ladles (Fig. 12c) are effective only when the metal stream from the exit of the ladle to the sprue and the sprue itself are shrouded in an inert gas, because the high discharge velocities from the ladle cause stream spreading and lead to oxidation and inclusion formation in air.

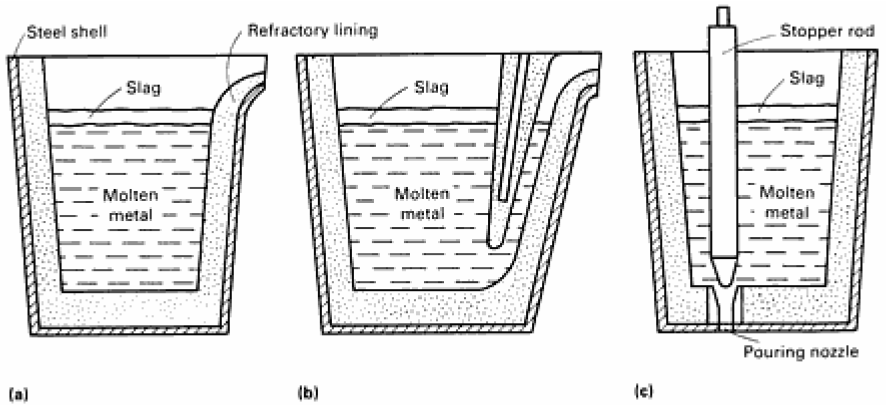


Fig. 12 Types of pouring ladles. (a) Open lip-pour ladle. (b) Teapot ladle. (c) Bottom-pour ladle

A variety of automatic pouring devices are available commercially that precisely and reproducibly fill the mold from ladles. The advantages of automatic pouring include improved consistency of pouring, increased productivity, reductions in pouring scrap, better process control, improved working conditions on the pouring line, and reduced environmental problems.

Venting. An important aspect of mold filling, often overlooked, is allowing the air in the mold to escape as the mold is filled. If air cannot easily leave the mold, it becomes compressed in the mold cavity and generates a back pressure against the flowing metal that holds up the metal, which may cause it to freeze or misrun before the mold cavity is filled. Passages placed in the mold so that air can escape during pouring are called vents. While it is obvious that impermeable molds, such as metal molds, need to be vented, it is less obvious that vents are needed in permeable molds, such as sand molds. However, venting is every bit as important in sand, especially in high-pressure molding lines.

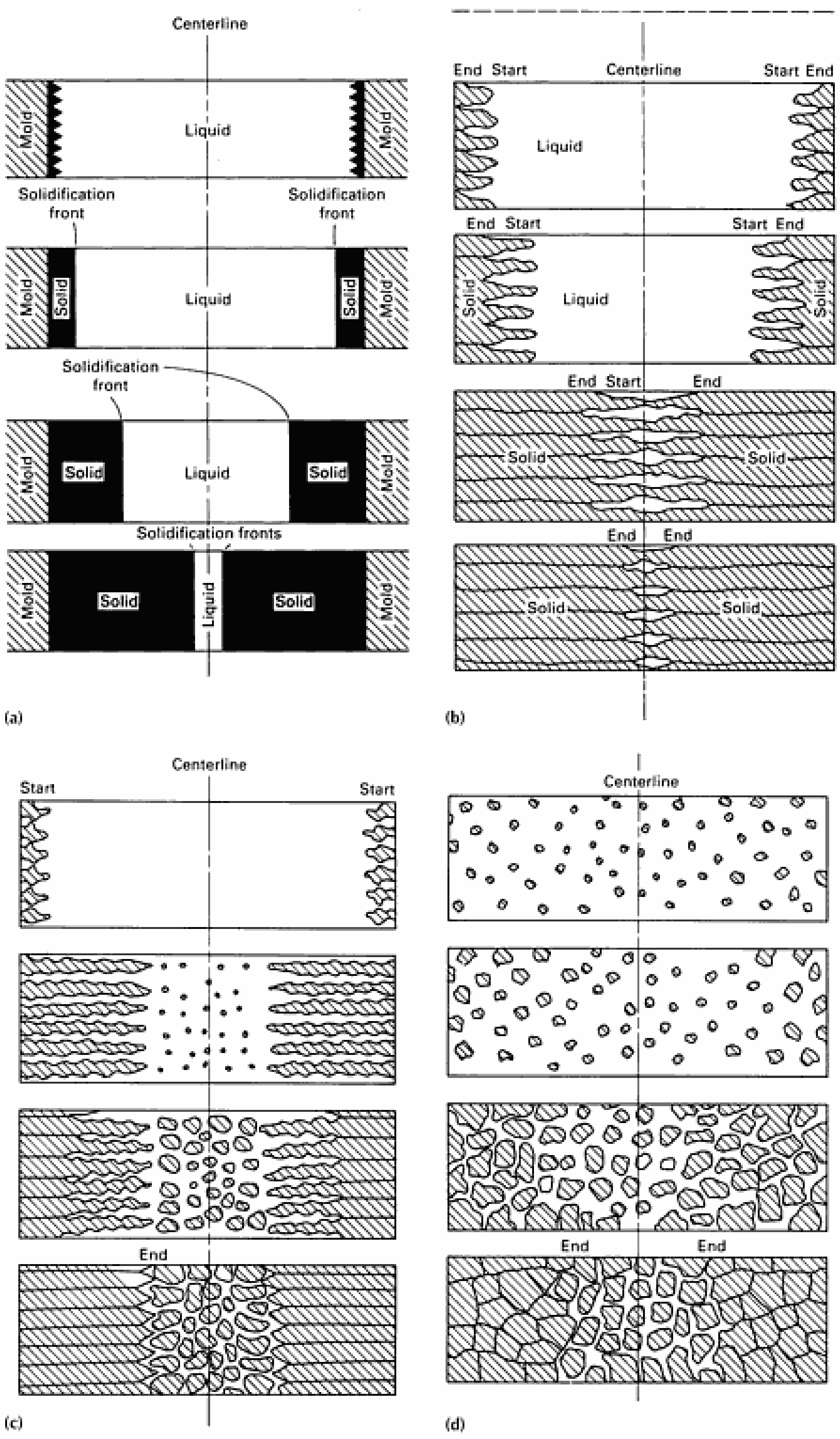
Vents should be placed at the highest point in the casting cavity and in any part of the cavity that will be cut off from the rest of the cavity as the casting fills. Vents should exit the mold on the cope surface. Open risers make excellent vents; however, if blind risers are used, they should be vented. Vents should also be placed at the end of runners. Parting line vents should be used only in vertical parting line molds. Large cores should be vented; if it is not possible to vent them directly to the atmosphere by cutting a hole in the mold, vent tubes (flexible plastic) should be run from the core to the top of the cope.

As the melting temperature of the alloy increases, the volume of air that expands on being heated by the incoming metal increases. Thus the size and number of vents should increase as the melting point of the metal increases (e.g., vents in steel castings should be larger and more numerous than those in aluminum castings).

Risering

Riser design deals with the sizing and placement of reservoirs of feed metal to compensate for the shrinkage that occurs during solidification. These reservoirs are called "risers" or "feeders." When liquid metal freezes, it undergoes three different volume changes: shrinkage of the liquid as it cools, shrinkage of the alloy as it transforms from liquid to solid, and shrinkage of the solid as it cools to room temperature. While the shrinkage accompanying the liquid/solid transformation occurs in a pure metal at a single temperature (the freezing temperature), it occurs over the range of temperatures between the liquidus and the solidus or eutectic temperature in alloys. Some of the volume change in alloy solidification is caused by segregation of alloying elements to the liquid during solidification. In addition, the mold cavity expands as it heats up when molten metal enters the mold. These effects mean that liquid metal must continue to be available during casting solidification to assure that no shrinkage voids form in the casting.

The distribution of liquid and solid in a casting section during freezing depends on the freezing range of the alloy. Pure metals, which freeze at a single temperature, freeze with a well-defined solidification front. In that part of the casting in which the temperature is below the freezing point, the casting is solid, and in the rest of the casting, it is liquid. However, as the freezing ranges of alloys increase, the freezing front becomes diffuse (Fig. 13). For a short freezing range alloy, such as steel, solidification begins with the formation of a skin of solid metal at the mold/metal interface, and there is a clear channel for metal to flow down to feed shrinkage. In these alloys, the only place where shrinkage is expected is at the centerline of the casting, which is the last part of the casting to solidify. In these alloys, tapering the casting cures the problem.



Centerline
Mold
Liquid
Mold
Solidification front
Solidification front
Mold
Solid
Liquid
Solid
Mold
Solidification front
Mold
Solid
Liquid
Solid
Mold
Solidification fronts
Mold
Solid
Liquid
Solid
Mold
(a)
End Start
Centerline
Start End
Liquid
End Start
Start End
Solid
Liquid
Solid
End Start
End
Solid
Solid
End
End
Solid
Solid
(b)
Centerline
Start
Start
End
(c)
Centerline
End
End
(d)

Fig. 13 Solidification (freezing) mode for pure metals and alloys. (a) Freezing mode in pure metals, in which the freezing range (liquidus-to-solidus interval) approaches zero. Crystallization begins at the mold wall and

advances into the casting interior on a plane solidification front. (b) Freezing mode in short freezing range alloys (<50 °C, or <90 °F). (c) Freezing mode in intermediate freezing range alloys (50 to 110 °C, or 90 to 200 °F). (d) Freezing mode in long freezing range alloys (>110 °C, or >200 °F).

For very long freezing range alloys (similar to many aluminum and copper-base alloys and superalloys), freezing begins at the walls, but grains quickly nucleate and grow throughout the entire casting, making feeding difficult. The result is that shrinkage is dispersed throughout the entire casting, usually in the form of microporosity. This situation can be alleviated by increasing the rate at which freezing occurs, but this is limited by how efficiently heat can be absorbed by, or transferred through, the mold. As refractory molds are generally poor conductors of heat, increasing the thermal gradient is generally effective only in thin sections, especially in high thermal conductivity alloys, such as aluminum- or copper-base alloys.

Gas solubility is a particular problem in some alloys. Hydrogen is easily picked up from atmospheric humidity in aluminum melts, and nitrogen may be picked up in steel melts. Unfortunately, the solubility of hydrogen in solid aluminum is about an order of magnitude less than it is in liquid aluminum. The result is that hydrogen gas is rejected into the liquid from the solidifying alloy and forms gas bubbles in the liquid; if these bubbles cannot escape from the casting, they appear in the casting as pores. Nitrogen gas porosity arising from a similar situation is sometimes found in ferrous castings, especially in the presence of certain resin binders that decompose and saturate the liquid iron with nitrogen.

The goal of risering is to encourage the casting to feed progressively, that is, to feed from a remote point in the casting toward the riser; so that shrinkage is fed and gas that dissolves in the liquid can escape (Fig. 14). Most castings, however, have complex shapes, which make it difficult to predict how solidification will proceed. However, an approximation can be made to help the metalcaster decide how to arrange and size risers. This approximation depends on the fact that solidification rate is proportional to the square of the ratio of the casting section's surface area to its volume. This relationship is referred to as Chvorinov's law, which is given by the relationship: $t = k \cdot (V/A)^2$, where k is a constant proportionality whose value is dependent on the thermal properties of the metal and the mold. In other words, the freezing time, t, is proportional to the square of the ratio of the section's volume to its surface area $(V/A)^2$. Therefore, a thin plate will solidify faster than a sphere of equal volume. In the same way, edges, corners, and fins on castings will solidify faster than straight sections, and concavities (internal corners and recesses in the casting) will solidify more slowly than straight sections. Because feed metal cannot flow through portions of the casting that have already solidified, the first rule to follow in establishing progressive solidification is not to attempt to feed a thick section through a thin section. Each thick (slow-to-solidify) section must be isolated from thin (fast-to-solidify) sections and provided with its own riser. The riser for these thick sections may require a gate; however, in many cases it is not feasible or economical to place a gate into the riser. In that case the riser is called a "blind" riser.

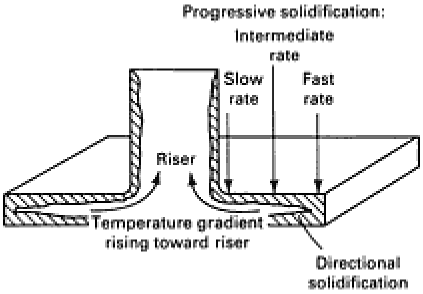

Progressive solidification:
Intermediate rate
Slow rate
Fast rate
Riser
Temperature gradient rising toward riser
Directional solidification

Fig. 14 Directional and progressive solidification in a casting equipped with a riser

For the riser to be effective, it must solidify after the casting section it feeds has solidified. This is assured by making the surface area to volume ratio of the riser greater than that of the casting section it feeds. There are a number of methods that can be used to estimate the size of risers that should be used for various alloys. Sizing the riser is usually done without regard to the molding system or aggregate used, as the thermal conductivity of the mold affects both the casting and the riser; and it is only the ratio between them that is of interest in the estimation process.

Considering only the amount of feed metal in a riser is not sufficient in riser design, the riser must also be able to deliver this metal to the areas of the casting where shrinkage occurs. The feeding distance of risers depends on the alloy and on the mold system used. The fact that the edges of the casting freeze faster than the riser means that they provide an "end effect." The heat supplied by the mass of the solidifying riser keeps the area around it liquid longer than it would otherwise be, providing a "riser effect" to extend its feeding distance. The combination of the end effect and the riser effect create progressive solidification from the edge of the casting to the riser. However, as the freezing range increases, the amount of solid coexisting in the area of the casting between the liquidus and solidus temperatures also increases, which makes feeding difficult. Feeding distance estimates are therefore particularly important in alloys with short freezing ranges, such as steels; there are a number of methods that have been developed to aid in this estimation. However, in long freezing range alloys, these methods are ineffective because feed metal flow is so difficult in the mushy region.

In long freezing range alloys, especially aluminum alloys, progressive solidification can be encouraged by using metal chills in combination with risers. The chills are placed in the mold adjacent to the casting surface, so that they can pull heat out of the casting in that area (Fig. 15). Risers are placed between the chilled areas of the casting to provide feed metal; these risers are often insulated so that their freezing rate is retarded even more. The object is to increase the thermal gradient in the solidifying metal so that the actual part of the casting at temperatures between the liquidus and solidus is as short as possible.

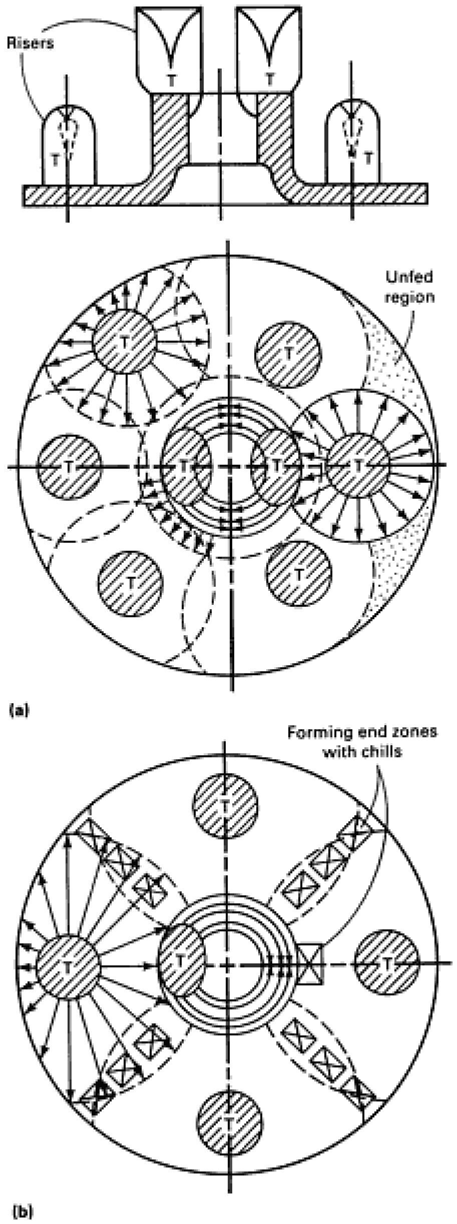


Fig. 15 Use of chills to reduce the number of risers (T) on a steel flange casting. (a) Side and top view of the casting illustrating locations of the eight risers used when the workpiece is divided into feeding areas without

considering end effects. (b) Top view of identical casting showing locations of five risers used when the workpiece is divided into feeding areas in which riser effect and end effect considerations are accounted for through the use of chills

One method of getting an accurate prediction of where shrinkage will form is to use commercial solidification simulation programs. These programs do not predict the size of the riser that will feed shrinkage in a casting, but they do show exactly how solidification will proceed. This means that the foundry must estimate the size of the risers by other means in designing the riser plus gating assembly. Some commercial programs include expert system routines to help foundry engineers design gates and risers and then check them using fundamental heat flow equations that are solved using finite difference or finite element methods.

The efficiency of risers can be significantly improved if they are surrounded by insulating or, in the case of copper-base and ferrous metals, exothermic materials. Exothermic materials react chemically in the presence of heat to produce more heat. The most common type of exothermic reaction is between iron oxide and aluminum powder: its reaction raises the temperature of the reactants to well above that of the melting point of steel. Exothermic riser "sleeves" contain a controlled amount of reactants, which slow solidification and maintain the riser at a temperature above its melting point for an extended period of time so that it is able to continue feeding the casting. In alloys with short freezing ranges, the risers solidify with a pronounced pipe in their center; care must be taken to be sure that the depth of the pipe does not enter the casting, causing scrap. Another way to improve riser efficiency is to cover the top of the riser with insulating or exothermic materials. This cover is especially important in ferrous metals, which lose substantial amounts of heat by radiation to the atmosphere. When the risers are covered by exothermic or insulating materials, this heat loss is effectively stopped.

Molding Methods

Thomas S. Piwonka, The University of Alabama

Classification of Molding Methods

MOLDING METHODS and materials encompass a wide range of options. Some molding (casting) processes are centuries old, while others did not exist two generations ago. The selection of the correct one to use in a specific casting application depends on the alloy, the dimensional tolerances desired, the quality of the casting, and the price the customer is willing to pay. Most metals and alloys can be cast using any of the methods. There are, however, limitations in some cases.

Foundry processes can be classified based on the molding medium, such as sand molds, ceramic molds, and metallic molds. This article uses such a classification system. Molding methods may also be classified based on whether the molds are permanent or expendable. Similarly, subclassifications can be developed from patterns, (i.e., whether or not the patterns are expendable). For permanent molding, processes can be classified by the type of mechanism used to fill the mold. Table 1 provides one possible classification system for commonly employed molding and casting processes.

Table 1 Classification system for foundry processes based on mold type

Expendable mold processes/Permanent patterns
Clay/water bonds (green sand molding)
Silica sand
Olivine sand
Chromite sand
Zircon sand
Heat-cured resin binder processes

- Shell process (Croning process)
- Furan hot box
- Phenolic hot box
- Warm box (furfuryl/catalyst)
- Oven bake (core oil)

Cold box resin binder processes

- Phenolic urethane
- Furan/SO_2
- Free radical cure (acrylic/epoxy)
- Phenolic ester
- No-bake resin binder processes
- Furan (acid catalyzed)
- Oil urethane
- Phenolic urethane
- Polyol urethane

Silicate and phosphate bonds

- Sodium silicate/CO_2
- Shaw process (ceramic molding)
- Unicast process (ceramic molding)
- Alumina phosphate

Plaster bonds

- Gypsum bond

No bond

- Magnetic molding
- Vacuum molding

Expendable mold processes/Expendable patterns

Foamed patterns

- Evaporative foam casting
- Replicast process

Wax patterns (investment casting)

- Ethyl silicate bonded block molds
- Ethyl silicate bonded ceramic shell molds
- Colloidal silica bond
- Plaster bond
- Counter-gravity low-pressure casting

Permanent mold processes

- Die casting
  - High-pressure die casting
  - Low-pressure die casting
  - Gravity die casting (permanent mold)[a]
- Centrifugal casting
  - Vertical centrifugal casting
  - Horizontal centrifugal casting
- Hybrid processes
  - Squeeze casting
  - Semisolid metal casting (rheocasting)

(a) When sand or plaster complex cores are used instead of metal cores, the term *semipermanent mold casting* should be used.

Of the expendable mold/permanent pattern processes listed in Table 1, green sand molding is the most prevalent. Expendable mold/expendable pattern processes use wax patterns (investment casting) or foamed plastic patterns (lost foam casting). The investment casting process is one of the oldest casting processes known (it has been used for more than 6000 years), while the lost foam process has been used commercially for less than 20 years. Permanent mold processes involve the use of metallic (usually ferrous) or solid graphite molds. On a volume basis, die casting and permanent mold casting are the most important.

Sand Molds

SILICA SAND, either bonded or unbonded, is the most popular molding media. Sand has the advantage of being widely available, inexpensive, able to withstand the elevated temperatures involved in casting most alloys, and easily recycled. In addition, it does not react with most metals and alloys, and it can be bonded with clay, resins, or silicate compounds. Because sand molds are permeable, the air displaced by the metal when it enters the mold can escape through the mold.

Bonded Sand Molds

In bonded sand molds, the sand particles are held together with chemical bonds. The bonds that are developed must be easily broken when the casting is solid so that the casting can be removed from the mold.

Green Sand Molds

Green sand molds are the most widely used of all sand molds. They are made of sand, bonded by a mixture of clay and water. Other materials may be added to the sand to control its strength and prevent metal penetration. The sand is called "green sand" because it is not baked or fired. Its actual color is usually black.

Patterns, Cores, and Molding Machines. The casting cavity is formed in the sand mold by compressing it around a pattern, which is a wooden, plastic, or metal form that has the shape of the casting, together with its gates, risers and core prints (Fig. 1). In bonded sand processes, the pattern is removed from the mold and used repetitively to make molds. The dimensions of the pattern are slightly greater than that of the castings because the casting shrinks during solidification. Castings distort as they cool, as a result of stresses produced by the resistance of the mold to casting shrinkage, so patterns must be designed to compensate for this distortion if accurate castings are to be produced. As the pattern will be removed from the mold after it is made, draft is added to vertical surfaces so that the pattern can be drawn from the mold without scraping the sides of the mold cavity.

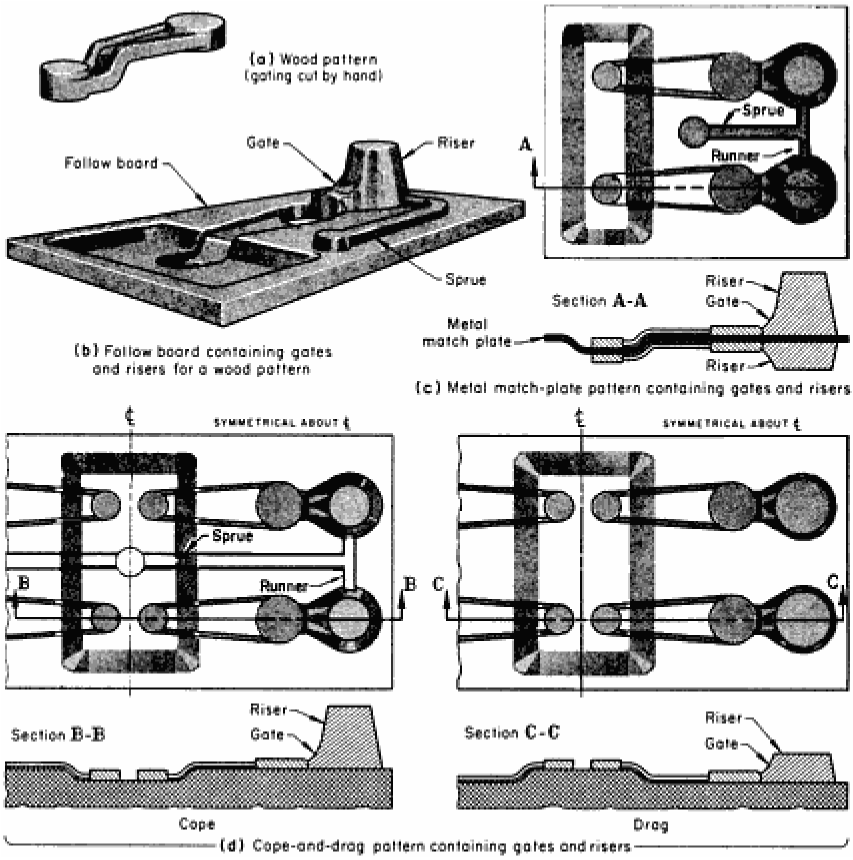

(a) Wood pattern (gating cut by hand)
Follow board
Gate
Riser
Sprue
(b) Follow board containing gates and risers for a wood pattern
Sprue
Runner
A
Section A-A
Metal match plate
Riser
Gate
Riser
(c) Metal match-plate pattern containing gates and risers
SYMMETRICAL ABOUT ℄
Sprue
Runner
B
B
C
C
SYMMETRICAL ABOUT ℄
Section B-B
Riser
Gate
Section C-C
Riser
Gate
Cope
Drag
(d) Cope-and-drag pattern containing gates and risers

Fig. 1 Patterns for a sand casting and its gating and risering systems, for four different methods of mold production

The choice of pattern material depends on the number of molds that are to be produced from it and the dimensional accuracy tolerances of the casting. For short runs or experimental castings, patterns may be loose pieces shaped in wood, in which case the gating will be cut in the sand by hand using tools designed for the process. In making a mold from a loose-piece pattern, the molder places the pattern on a flat mold board to support it during molding. The bottom, or drag half is made first. A mold box is placed on the board to contain the sand. Prepared sand (mixed with clay, water, and additives) is placed in the mold and compacted using a ramming tool. When the entire mold is filled with sand and completely compacted, the mold is turned over and the pattern withdrawn. The procedure is repeated for the cope half of the mold. The cope is placed on the drag, and metal or wooden "jackets" are placed around the parting line to align the two halves and prevent metal from running out of the mold at the parting line. Weights are placed on the mold before pouring to prevent the cope from floating on the liquid metal when the casting is poured.

Cores are used to make the hollow parts of castings, such as the holes of a pipe fitting or the air path in an automotive intake manifold. The cores are usually bonded with resins, which are stronger than the clay-water bond used in green sand. The cores are supported in the mold by extensions at either end. These extensions rest in core "prints" in the green sand. The prints not only support the cores, they also position them accurately to maintain casting dimensions. Cores are placed in the drag half of the mold after the pattern is drawn from the mold and before the cope is placed on the drag to close the mold.

Match-plate patterns are split patterns in which the pattern that will make the cope is on one side of the plate, and the pattern that will make the drag is on the other side. Match-plate patterns are used on mechanized molding machines for intermediate runs of moderate sized castings. More than one casting may be made in a mold, with the sprue, gates, and risers shared among the castings. In match-plate machine molding, the sand is introduced into the molding box, and the pattern is placed on a machine table. The machine then raises the table a few inches and then lets it fall back freely by gravity. The sharp jolt experienced by the sand when the machine table stops falling compresses the sand in the box. The procedure is repeated a number of times until the sand is properly compressed. Usually the mold is then subjected to a squeeze pressure from the top (the part of the mold away from the pattern face) of the mold half to further compress the sand.

For large castings and very high production runs, cope and drag patterns are used on highly automated molding machines. The cope pattern is separate from the drag pattern, and separate molding stations are used to make each mold half. Metal flasks hold the sand. Cores may be placed in the molds by hand or by using automated fixtures. In some machines, only squeezing is used to compact the sand; in others, both jolting and squeezing is used. Figure 2 shows a jolt-squeeze machine. Parting lines may be either horizontal or vertical (Fig. 3).

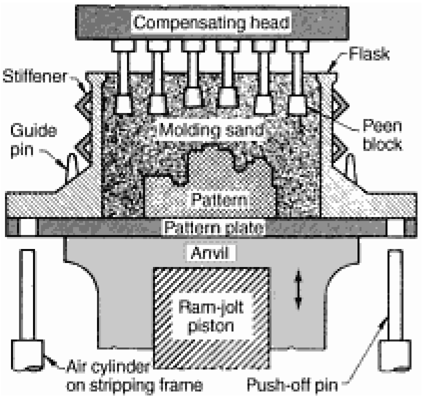


Fig. 2 Essential components of a high-pressure jolt-squeeze molding machine. The compensating head equalizes the pressure applied to each floating peen block as the sand filled flask is hydraulically raised against the peen blocks. This develops a uniformly dense packing of molding sand against the entire surface of the pattern.

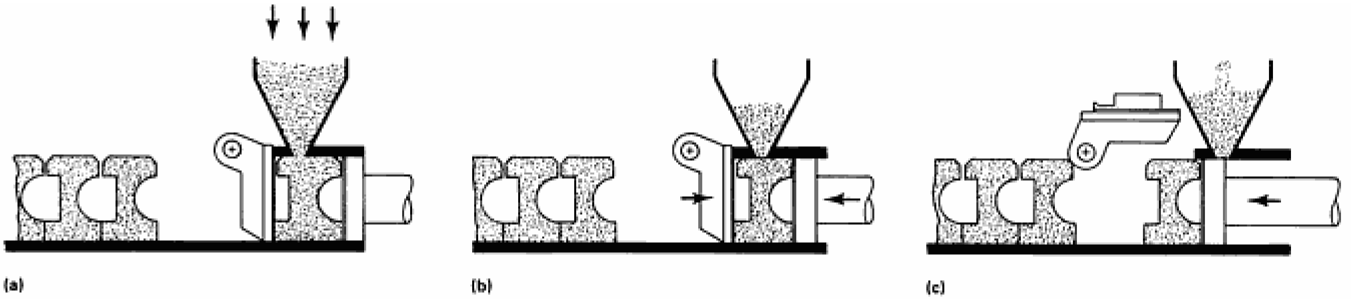


Fig. 3 Blow-fill pressure squeeze molding machine making vertically parted molds (a) Molding chamber filled with sand. (b) Sand compacted by squeeze pressure. (c) Finished sand mold pushed out of molding chamber

Impact molding machines use rapidly released compressed air above the sand in the pattern box to send a shock wave through the sand to compress it (Fig. 4). The flask is filled with sand by gravity and sealed against an air chamber before the compressed air is released. Advantages of the impact molding process are highest mold density at the parting line and pattern surface, uniform mold strength across the mold, and less pattern wear than with other processes.

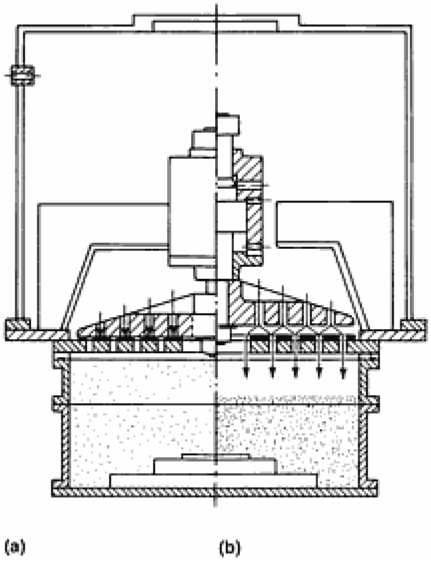


Fig. 4 Pressure wave molding machine that compacts sand by the rapid release of air pressure or an explosive combustible gas mixture. Part (a) shows the mold filled by gravity prior to being compacted by the pressure wave at (b).

Flaskless molding machines are popular, using either horizontal or vertical parting lines. Only squeeze pressure is used to compact the sand. Cope and drag halves may be made simultaneously, and the mold halves are made in the same attitude as they will be used, so there is no need to rotate the molds.

When molten metal is poured into a green sand mold, the moisture at the mold/metal interface flashes into steam. This rapid expansion in volume (liquid transforming into vapor) flushes the air away from the interface. The air and the expanding water vapor must escape from the mold. In high-density molding processes, such as impact molding, the permeability of the mold is not sufficient, and vents must be cut into the mold to prevent the back pressure from the gases from blocking the entrance of the molten metal and causing the casting to only partially fill with metal.

Sands. The aggregate usually used in green sand casting is silica sand, usually from former lake bottoms or river bank deposits. Sand is usually 99% silica in the form of quartz, with the balance being oxides of iron, aluminum, titanium, magnesium, and calcium, depending on the source of the sand. Quartz undergoes a series of crystallographic transformations as it is heated and expands in a nonlinear manner with temperature (Fig. 5). These transformations can cause dimensional problems if not compensated for in the casting process. Sand grains may be rounded, subangular, or angular in shape. Rounded grains flow more easily and pack more densely; they also use less binder because their surface area to volume ratio is smaller than other shapes. However, molds made from them have less permeability. As sand is cycled through the system, it wears and eventually becomes too small to be used and must be discarded.

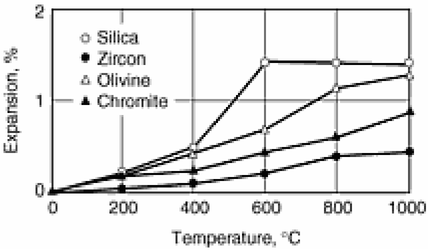


Fig. 5 Expansion characteristics of various foundry sands

Sand used for molding is usually held within strict size and size distribution limits. The sand size is determined by passing a sample of sand through a series of successively finer screens, and weighing the amount collected on each screen. The best combination of properties of green sand is usually found when almost all of the sand is caught on three or four adjacent screens; however, two screen sands have been used successfully for certain casting processes.

Clays. The sand is bonded by a clay/water mixture. Clays used in the United States are naturally occurring montmorillonites, sodium (Western) bentonite and calcium (Southern) bentonite. Western bentonite is the most commonly used clay. It develops a lower green strength than Southern bentonite (Fig. 6) but has higher strength at casting temperatures (Fig. 7). Southern bentonites, however, allow the sand mixture to flow more evenly over the pattern and thus aid the molding operation. Usually, a foundry will prepare a mix of both Southern and Western bentonites to achieve a sand that is optimized for the castings it makes. The sand, water, and clay are mixed in a muller for a period of one to two minutes; during this time the clay/water mixture coats the sand. Water added to the clay may be driven out by the heat of the solidifying casting. When this happens, the clay loses its bonding ability. Water may be added to the clay to reconstitute it as long as the clay has not reached a temperature greater than 600 °C (1110 °F). Because the clay adjacent to the molten metal has reached that temperature, and the clay in cooler portions of the mold has not, a portion of the clay must be replaced. The amount of clay and water added in the muller must be sufficient to bond new sand that is added on each cycle (including recycled core sand, which was previously bonded using resins) and to compensate for the moisture and clay burn out in the previous casting cycle.

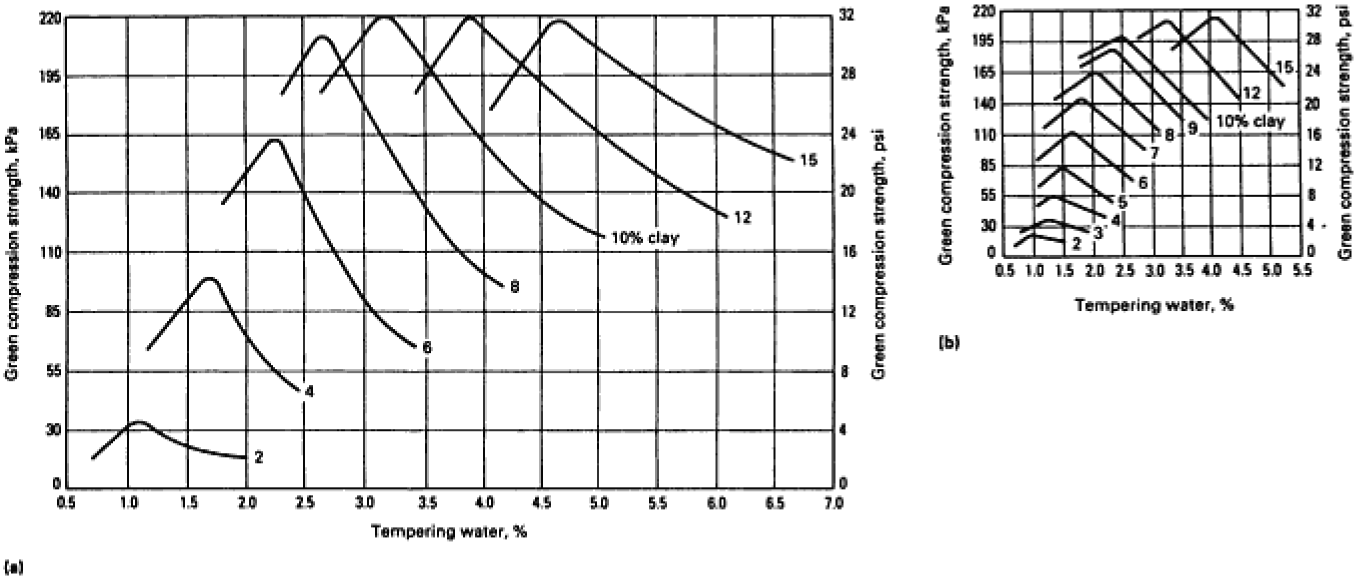


Fig. 6 Variation of mold sand properties with water content. (a) Southern bentonite. (b) Western bentonite

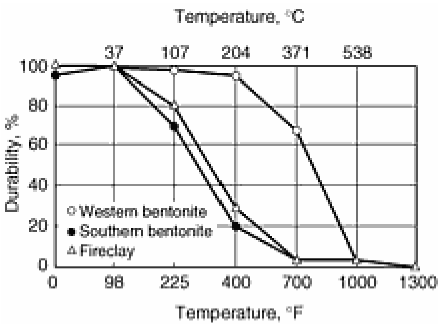


Fig. 7 Effect of casting temperature on the durability (strength) of various foundry sands

Sand Additives. Other materials are added to the sand to improve its performance. Chief among these materials for ferrous alloys is seacoal, which is powdered bituminous coal. Seacoal cokes when it is heated, plastically expanding and filling the interstices between the sand grains at the casting surface, thus preventing penetration of molten metal into the sand. In addition, it burns, assuring that the atmosphere at the mold/metal interface is reducing; so that fayalite, a low melting point solution of iron oxide and silica, does not form on steel castings. Cellulose may be added in amounts up to 0.2% to absorb excess water and control sand expansion. Polymers may be added to control the surface energy of water so that it coats the sand grains more effectively, and soda ash may be added in very small amounts to control the pH of the sand mixture.

Sand Testing. Sand is tested to assure its quality. Normal tests include mechanical properties, usually expressed as "compactability," moisture content, active clay content, and volatile content, tested as "loss on ignition." Incoming sand is tested for grain fineness number, a measure of both size and size distribution, and it may be tested for acid demand value, especially when certain resin binders are used for cores.

Sand Reclamation. Sand is normally reclaimed and reused. When the casting is poured, the sand next to the molten metal is heated above 600 °C (1110 °F), the water evaporates, and the clay at the interface can no longer be used as a bonding agent. However, most of the sand and clay in the mold is not significantly heated by the solidifying metal and can be recycled. The sand is separated from the castings, cooled, and recycled through the muller, where new sand (to compensate for sand lost by attrition), water, and clay is added. If pieces of core in which the resin binder has not decomposed are present, they are crushed. Metal and other debris (such as core rods) are removed by magnets, and the sand is screened before being added to the muller. It is important to cool the sand to a temperature below 50 °C (120 °F) for the clay-water bond to work properly. The amount of makeup water and clay added depends on the sand to metal ratio in the mold; obviously, larger and heavier castings will burn out more moisture and clay than lighter castings.

The recycled sand includes cores bonded with resins, which may not be completely burned out. If the resins are not completely removed from the sand grains, they interfere with the clay-water bond. The only way to completely remove these resins is to thermally reclaim the sand, heating it to temperatures greater than 650 to 825 °C (1200 to 1500 °F) in air. These temperatures, of course, also burn out the bentonites; for this reason, only a portion of sand may be thermally reclaimed on any cycle. Note that the core sand is added to the system on each cycle. Frequently, the core sand addition is all that is needed to make up for sand losses in processing.

Sand Handling Systems. In a high production foundry, transporting the sand from mulling to molding to pouring to shakeout to recycling and back to mulling requires a large sand handling system comprising conveyor belts, storage areas, and the sand mixing and molding equipment. Sand should not be blown into silos or bins because blowing causes the sand to segregate by size, destroying its size distribution. Dust from sand systems must be removed from the foundry air, and sand temperature must be controlled. Fines in the sand must also be removed because their high surface area will absorb clay and moisture and drastically change sand properties. Controlling the sand system may be difficult if there are wide swings in the size of castings poured during a shift. The sand-to-metal ratio is constantly varying, making it difficult to predict just how much moisture and clay to add to the muller.

Dry Sand Molds

Dry sand molding is sometimes used to make large castings, although resin-bonded molds have largely taken over for this process. In dry sand molding, the water is removed from the mold prior to pouring. The bond is created both by using bentonites, and also through the use of other organic binders, such as dextrin, molasses, glutrin, or pitch. The molds are baked in ovens prior to pouring to drive out the moisture. Baking temperature and time depend on the size of the mold and the binder used. Dry sand molds are generally stronger than green sand, and they usually have better dimensional stability than green sand in larger castings. Sand grain size is usually coarser in dry sand molding, to allow the increased permeability of the mold to aid in mold drying. Therefore, mold washes and coatings are often applied to improve surface finish.

As an alternative to drying the entire mold, only the surface of the casting cavity may be dried. These "skin-dried molds" are made from the same sand mixtures as dry sand molds, but only the surface that will contact the molten metal is dried to a depth of 6 to 12 mm ($\frac{1}{4}$ to $\frac{1}{2}$ in.).

Resin-Bonded Sand Molds

Over the last thirty years, a number of resins have been developed as binders for sand, primarily for making cores, although they are also used as molds. These binder systems generally fall into one of the following categories: no-bake, cold box, protein, hot/warm box, and shell (Croning). In these processes, sand and binder are mixed together and formed around a pattern or placed in a core box. The resin may be cured by heat, or it may be cured by the setting of the resin. To accelerate the curing of the resin, catalysts may be added, either in solid, liquid, or gaseous form.

No-Bake Processes. The term "no-bake" generally refers to all of the binder systems in which a gas catalyzes the resin while the sand is in contact with the core box or pattern. Originally it referred only to the phenolic-urethane-amine process, which is still the most popular core resin in use. In addition to the phenolic urethane process, other no-bake binder systems include furan acid catalyzed, phenolic acid catalyzed, ester-cured, and alkyd-urethane binders. Furan binders depend on the use of furfuryl alcohol, either by itself or modified with urea, phenol, formaldehyde, or other additions. The binders cure at room temperature by the addition of an acid catalyst, and they have reaction products, such as nitrogen gas and water. The amount of binder used must usually be minimized, both for economic reasons and to limit the amount of nitrogen gas picked up in ferrous castings, where it can case pinholes, and water vapor picked up in nonferrous castings, where it causes microporosity. The catalyst used depends on the rate of cure required and the type of metal cast. Urea-containing binders react relatively quickly, and a popular catalyst for them is phosphoric acid. Sulfonic acids may be used for low-nitrogen binders. Sulfuric acid may also be used, although it is not recommended for use with ductile iron, where the generation of sulfur fumes during pouring causes the formation of flake graphite. Binder addition is generally 0.8 to 2.0% of the weight of the sand, and the catalyst addition is between 20 and 60% of the binder weight.

Phenolic binder systems are based on resole phenolic resins, which contain phenol, formaldehyde, and modifying additions in water. These are cured with sulfonic acid, added at a level between 20 and 45% by binder weight.

Ester-cured phenolic binders are popular in steel foundries because they contain no furfuryl alcohol or nitrogen and do not use sulfur for curing. The two-part binder consists of the water-soluble alkaline phenolic resin, plus 15 to 30% liquid ester coreactants. A blend of esters is used to provide the required setting time but only partially cross-link the resin. Thus, the resin retains a small degree of thermoplasticity, which permits the sand to absorb some expansion and reduces expansion defects in the castings.

Alkyd urethane binders, also referred to as oil urethane binders, are three-part systems used for large molds that require longer setting times. The three components are the following: part A, an alkyd oil resin; part B, a liquid amine/metallic catalyst; and part C, a polymeric isocyanate, such as polymeric methyl di-isocyanate (MDI). Part A is usually used between 1 and 2% by weight of sand, and part B is used between 2 and 10% of the weight of part A. Part C is added between 18 and 20% of part A by weight. Curing takes place in two stages: first the polymeric isocyanate reacts with the alkyd resin at a rate controlled by the amine catalyst. This reaction produces a bond that is strong enough to allow the pattern to be stripped. The second stage is the oxidation polymerization of the alkyd resin by atmospheric oxygen, accelerated by the metallic elements in the catalyst. Because oxygen must diffuse into the sand, this latter cure is a function of sand section thickness. The oxidation reaction can be accelerated by heating to between 150 and 200 °C (300 to 400 °F).

The phenolic urethane no-bake system is a three-part system consisting of the following: part I, a phenol formaldehyde resin dissolved in solvents; part II, a polymeric isocyanate dissolved in solvents; and part III, a liquid amine catalyst. The resin and the isocyanate combine to produce a urethane bond. However, unlike the alkyd urethane system, there is no second stage reaction and a deep through cure is obtained. Binder levels of 0.7 to 2.0% of the sand weight are recommended, with a ratio of 55 to 45 or 60 to 40, part I to part II. The amount of catalyst required is between 0.4 and 0.8% of the weight of the part I resin.

Cold Box Processes. The term "cold box" generally refers to processes in which the sand, binder, and catalyst are mixed together before the sand mixture is introduced into the core box or pattern; in this case curing begins immediately, and working time is limited. Cold box processes have become popular in high-production foundries. The original process is the phenolic urethane process. It is similar to the phenolic urethane no-bake process described above, except that the catalyst is introduced as a vapor after the core is blown, producing a rapid cure, which enhances production rates. Both di-methyl-ethylamine (DMEA) and triethylamine (TEA) catalysts are used. In this process, shown schematically in Fig. 8, a gassing system is used to meter out a predetermined quantity of liquid, change it to vapor, combine it with a carrier gas in the correct ratio, and deliver it to the core box. A scrubber system is also used to prevent the discharge of the offensive odor of the catalyst into the work area. Core box design must include consideration of the location of the catalyst vents to assure complete coverage of the core by the catalyst.

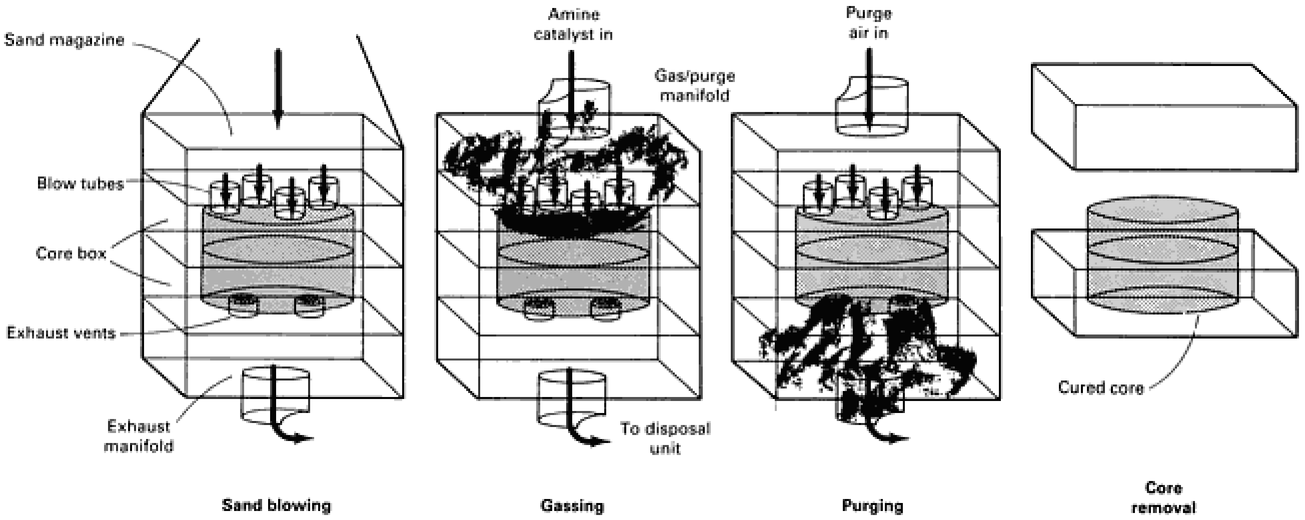


Fig. 8 The cold box coremaking process. The wet sand mix, prepared by mixing sand with the two-component liquid resin binder, is blown into the core box. The core box is then situated between an upper gas input manifiold and a lower gas exhaust manifold. The catalyst gas enters the core box through the blow ports or vents and passes through the core, causing almost instantaneous hardening of the resin-coated sand. The core is ready for ejection from the core box after purging with clean air for a few seconds. After the catalyst gas passes through the core, it leaves the core box through vents into the exhaust manifold. From the gas exhaust manifold, the catalyst gas is piped to an appropriate disposal unit.

The sulfur dioxide (SO_2) process uses a furfuryl alcohol/formaldehyde resin mixed with peroxide, such as methyl ethyl ketone peroxide (MEKP), and additives. The sand is mixed with these substances, and after being compacted in the core box, SO_2 gas is passed through the core. The sand has a long bench life, but sulfur-containing binders are not recommended for ductile iron, as they cause flake graphite to form in the metal.

The free radical cure (FRC) process uses three parts: a vinyl unsaturated urethane oligomer, an organic peroxide, and a vinyl silane adhesion promoter. The mixture is cured with SO_2 gas, which breaks down the peroxide, which in turn releases free radicals that cure the resin. The binder contains no nitrogen or water, which decreases gas defects in castings, but it is susceptible to mold erosion in ferrous castings.

The ester-cured phenolic process is similar to that of the no-bake ester-cured system. Here, however, the catalyst is methyl formate, carried by air. The cured strength is not quite as high as the urethane cold box system, but it is satisfactory for many applications, especially for making molds as a replacement for green sand.

Protein-Based Binders. One drawback to the use of organic binders is that the binders must be completely burned out during cooling of the casting if the sand is to be fully recovered. In very large cores, or, in the case of nonferrous alloys where the mold and core temperatures do not get sufficiently high so that the resins burn completely, core butts remain that must be crushed and the sand thermally reclaimed (burned) at high temperatures. In addition, cores not used for production must be put through the same process to reclaim the sand; unfortunately, the value of the resin is lost. A recent development to overcome this problem is the use of a protein-based binder.

The binder is a proprietary mixture of biopolymers, which do not break down thermally to produce toxic gases. Metal oxide catalysts are used to accelerate the curing reaction. In addition, the cured binder is water soluble, which means that unused cores and core butts may be treated with water to recover both the binder and the sand, without using thermal treatments. This binder was designed for use in nonferrous (aluminum and magnesium) applications, so it readily breaks down thermally at the lower solidification temperatures encountered in these alloys. Cores made with it have mechanical properties comparable to traditional organic binders. The process also yields castings with similar surface finishes.

Temperature Control during Coremaking. Temperature control is very important during the non-heat-cured coremaking processes. Curing is a chemical reaction, which doubles in rate roughly every 10 °C (18 °F). In other words, attempting to use these processes at too low ambient temperature (below 20 °C, or 70 °F) will slow the reaction rate and cause an incomplete cure and low strength. Increasing the amount of resin to compensate for the low temperature merely increases the amount of gas generated during pouring and leads to gas defects in the casting. Too high a temperature (above 30 °C, or 90 °F) shortens bench life and reduces sand properties. For consistent production during both hot and cold weather, sand heaters and coolers are essential. A sand heater should regulate the sand temperature to within 1 °C (2 °F) under normal conditions. Coremaking carried out under close temperature control minimizes the use of binder and catalyst, produces more uniform cores, and decreases foundry scrap.

In the hot box process, the binder-sand mixture is wet. A liquid thermosetting binder and a latent acid catalyst are mixed with dry sand and blown into a heated core box. Upon heating, the catalyst releases acid, which induces rapid cure; therefore the core can be removed in 10 to 30 s. After the cores are removed from the pattern, the cure is complete, as a result of the exothermic reaction and the heat absorbed by the core. Large cores require post curing in an oven.

Hot box resins are classified simply as furans or phenolics. Furans contain furfuryl alcohol, and phenolics are based on phenol, while furan-modified phenolics have both. All conventional hot box binders contain urea and formaldehyde. The furan hot box resin has a fast cure compared to that of the phenolic-type system and can therefore be ejected faster from the core box. Furan resin also provides superior shakeout and presents fewer disposal problems because of the lack of phenol. Typical resin content is 1.5 to 2.0%.

A simplified hot box reaction mechanism is liquid resin + catalyst + heat = solid resin + water + heat. The heat is provided by using a heated pattern or core box. Catalyst selection is based on the acid-demand value and other properties of the sand. Sand temperature changes of 10 °C (18 °F) or five units in acid-demand value of the sand require a catalyst adjustment to maintain optimum performance. Both chloride and nitrate catalysts are used. The chloride catalyst is the more reactive. Hot box pattern temperatures are 230 to 290 °C (450 to 550 °F), and the patterns are designed for use between 220 and 245 °C (425 to 475 °F). Running the pattern temperatures higher than this range produces patterns or cores with weakened or friable surfaces, which produce castings with poor surface finish. Hot box resins have a limited shelf life and increase in viscosity in storage. They should be stored in temperature-controlled areas. Hot box catalysts have indefinite shelf life.

Warm box resins are minimum-water (%) furfuryl-alcohol-type resins formulated for a nitrogen content of less than 2.5%. Because the resin/sand mix exhibits a high degree of rigid thermoset properties when fully cured, little or no post-strip distortion or sagging occurs. High hot and cold tensile properties are characteristic of warm box sands and generally permit a binder level between 0.8 and 1.8%, or about 20% less than the conventional hot box resin content. Warm box catalysts are copper salts based primarily on aromatic sulfonic acids in an aqueous methanol solution. The catalysts are unreactive with the resin at room temperature but form strong acids when heated. Pattern temperatures range from 150 to 230 °C (300 to 475 °F); the process was designed for use at 190 °C (375 °F).

The shell molding or "Croning process" uses a very fine sand coated with a thermosetting resin to produce a shell mold only about 10 mm (0.4 in.) thick. The very fine sand produces an excellent surface finish on the casting. Use of sand of such fineness would not be possible in a conventional mold because mold permeability would be too low; however, in a thin shell mold, it is not a problem.

The sand grains are coated with phenolic novolac resins and hexamethylenetetramine. The dry, free-flowing sand is coated by being mulled at 150 to 280 °C (300 to 535 °F) for 10 to 30 s. The coated sand is then placed in a dump box, and the box is rotated leaving the sand in contact with the hot pattern for a period of time. Pattern temperatures are generally between 205 to 315 °C (400 to 600 °F). The thickness of the shell produced depends on the amount of time the sand is in contact with the pattern. Dump boxes produce shells of variable thickness, and many shell mold foundries use the more expensive, but more accurate and controllable, contour patterns, in which the sand is blown between a heated pattern plate and a heated profiled back plate. Pattern halves are glued together before pouring and may be poured in either the vertical or horizontal position. Because the molds are only a thin shell, they are often supported during pouring, either in fixtures or in loose sand. Patterns may also contain shell cores.

In making shell cores, the sand is injected into a heated core box and then dumped out after a short time. Again, the thickness of the shell is dependent on the time in contact with the heated core box. Shell molds and cores generally produce castings with better surface finish and more accurate dimensions than other organic resin-binder processes.

Quality Control of Resin-Binder Processes. In all organic resin processes, care must be used to prepare the pattern or core box and to maintain it free from resin buildup during the production campaign. It is especially important to inspect the vents on a regular basis to be certain that they remain clear of resin products that could clog the vents.

Complex core geometries may be formed by gluing two or more cores together before they are placed in the mold. Alternatively, one core may be injected around another core to make the core assembly, thus avoiding the gluing operation. Cores are supported in the mold by extensions, called core prints, which extend into the mold. The mold holds the core prints firmly during pouring. Because cores are less dense than the molten metal, the pressure of the metal forces them upward in the mold, displacing them from their desired position. Small metal spacers, called "chaplets," are placed between the mold and the core to keep the correct position. These chaplets normally are melted by the molten metal and become part of the casting.

Sodium Silicate Bonded Sand (The CO_2Process)

Sand can be bonded using sodium silicate ("waterglass"). Sodium silicate binders are odorless and produce no volatile organic compounds when metal is poured into molds. The amount of silicate binder varies from 3 to 6% by weight, depending on the type of sand, its grain fineness, and the amount and type of contaminants present in the sand. Normal sand handling equipment can be used to prepare the sand. The sand has reasonably good bench life, but if impurities such as ferrosilicon or lime are present in the sand the bench life is shortened. As in resin-bonded sands, the sand is mixed (care should be taken not to overmix the sand, which will produce a crumbly mixture), placed around the pattern, and vibrated to compact it. The sand is then gassed with carbon dioxide gas (hence the name "CO_2 process"), which hardens the mold almost immediately. Molds are cured 24 h at room temperatures in dry conditions (high humidity softens the bond). During this time, their strength increases as a result of some dehydration of unreacted silicates and continued gelling of the silicate. They have good shelf life thereafter.

Sodium silicate foundry binders are metastable solutions. There are two hardening mechanisms that take place. First, there is dehydration by evaporation. Second, the reaction with CO_2 removes the sodium oxide from the silicate, and the silicate gels. Overgassing forms sodium bicarbonate and sodium carbonate, which embrittle the gel.

Both ferrous and nonferrous metals and alloys can be poured into these molds. To improve shakeout and core removal, organics, such as sugars, starches, or other carbohydrates, may be added to the mold. However, these accelerate the deterioration of mold strength in high humidity conditions. This molding method is often used for larger molds. A drawback is that sand reclamation is difficult. A combination of mechanical reclamation and water reclamation has shown promise, but recovery rates are limited to about 70%. An additional problem with the use of sodium silicate is that core removal is difficult because the bond does not break down on exposure to heat. Cores must be removed either chemically or mechanically.

Core boxes and patterns for sodium silicate molds may be made of wood, metal, or plastic, and they must be washed thoroughly after use to prevent a buildup of sodium silicate. Mulling equipment and ramming tools must also be washed thoroughly after use. Sand mixes that have not been used should be covered with a wet cloth to prevent a hard surface crust from forming because the mixture will slowly cure in air.

Mold Washes and Coatings

Under certain circumstances, molten metal can penetrate the spaces between the sand grains into the sand mold, forming a rough surface on the casting. In steel castings, iron or manganese oxide may form on the surface of the molten steel and react with the silica sand to form a glassy compound. In both cases, the resulting casting surface may cause the casting to be unusable. To prevent this condition, called metal penetration, ceramic coatings are often applied to areas of the mold or core where penetration is likely to be found. These coatings normally consist of aqueous slurries containing finely divided ceramic particles. Nonaqueous slurries are used when the ceramic in the coating is hygroscopic or reacts with water. The small particle size of the ceramic fills the space between the sand grains, which prevents molten metal from entering the mold. Coatings may also be used to produce a smoother surface on the casting than would be obtained if the casting were poured in an uncoated mold.

The ceramics in the slurries are selected on the basis of their nonreactivity with iron oxides. Mullite, zircon, alumina, magnesite, and graphite refractories are often used. The choice of the refractory depends on the alloy being poured. Most coating compositions are proprietary, and they are often developed for a specific use. Coating slurries may contain other additives to improve flowability and shelf life. Coatings may be applied to the entire mold or core, or only used in areas where penetration is likely to occur, such as re-entrant angles where heat is concentrated in the casting, or in the drag half of the mold where metallostatic pressure is higher. Penetration defects are generally the result of using a too coarse molding sand or not ramming it tightly enough. However, in cast iron, the most common cause of penetration is graphite expansion near the end of solidification, which forces remaining liquid metal into the sand. This penetration can be cured by changing the solidification pattern so that the casting freezes progressively towards the riser.

Coatings may be applied by painting, spraying, dipping, or electrostatic means. In high production foundries, coatings may be applied to cores using robots or automated dipping lines.

Sand Reclamation

While it is assumed that the resin binder used in molds and cores burns off during solidification, this process is limited by the size of the core in relation to the size of the casting. For example, where the casting volume is large in relation to the size of the core, there is sufficient heat generated during solidification to burn off the resin. On the other hand, if the core is large in relation to the volume of metal, parts of the core may never heat up enough to cause the resin to decompose. The metal poured also influences resin decomposition; for example, steel is more effective than aluminum in generating enough heat to burn the resin. In addition, there may be a number of inorganic contaminants carried along with the sand or formed from chemical reactions during pouring. Residual resins and these contaminants interfere with the clay-water bond. One way of dealing with this interference is to discard a portion of the sand during each cycle and depend on a new sand addition to give the system sand and the molding properties desired.

However, disposal of spent foundry sand is becoming more difficult as landfills close and environmental regulations become more restrictive. As a result, the cost of sand disposal is a significant percentage of sand system operation. This expense has led to the development of methods of reclaiming sand instead of discarding it. Three primary methods are used: pneumatic, mechanical, and thermal.

In pneumatic methods, the sand is blasted in a high-pressure air stream against a steel or refractory plate. The impact of the sand on the plate causes the resin or silicate coating on the sand to physically separate from the sand grain. In mechanical systems, the sand is fed against a slowly revolving very large grinding wheel, which abrasively removes the coating. It is important to aggressively remove fines from pneumatic and mechanical processes to maintain the sand system operating characteristics. In the thermal method, the sand is fed into a fluidized bed operating from 680 to 800 °C (1250 to 1470 °F), and the resin burns off. In the thermal method, combustion of the resin and the carbonaceous additives to the sand also contribute to the heat of combustion, which lowers fuel requirements.

The relative economics of these processes depends on the amount of sand being reclaimed, the cost of energy at the foundry, and the type of contaminant being removed. In some cases, sand reclamation may be less expensive than the purchase of new sand. Thermal treatment may be combined with either the pneumatic or the mechanical treatment to reclaim a higher percentage of the sand. Sand that is thermally reclaimed is normally purer silica than naturally occurring sand, because other minerals may no longer be present.

Unbonded Sand Molds

It is not always necessary to use a binder with sand. In unbonded sand molds, the pattern form is held either by the pattern itself during pouring, or by the use of a vacuum. Unbonded sand molds have the advantage because they need no binders, mulling equipment, or mold additives.

Lost Foam Casting

In the lost foam process, patterns are made of expanded polystyrene or other foamable plastic or blend of plastics. The patterns are attached to a gating system, also made of foamed plastic, placed in a flask, and sand is vibrated around them. The molten metal is poured directly onto the plastic, which melts or burns. The metal replaces the foam pattern, taking its shape. This method eliminates the use of sand binders, additives, and cores, and it is capable of making some shapes that could be made no other way. Steps in the sequence are shown in Fig. 9, 10, and 11.

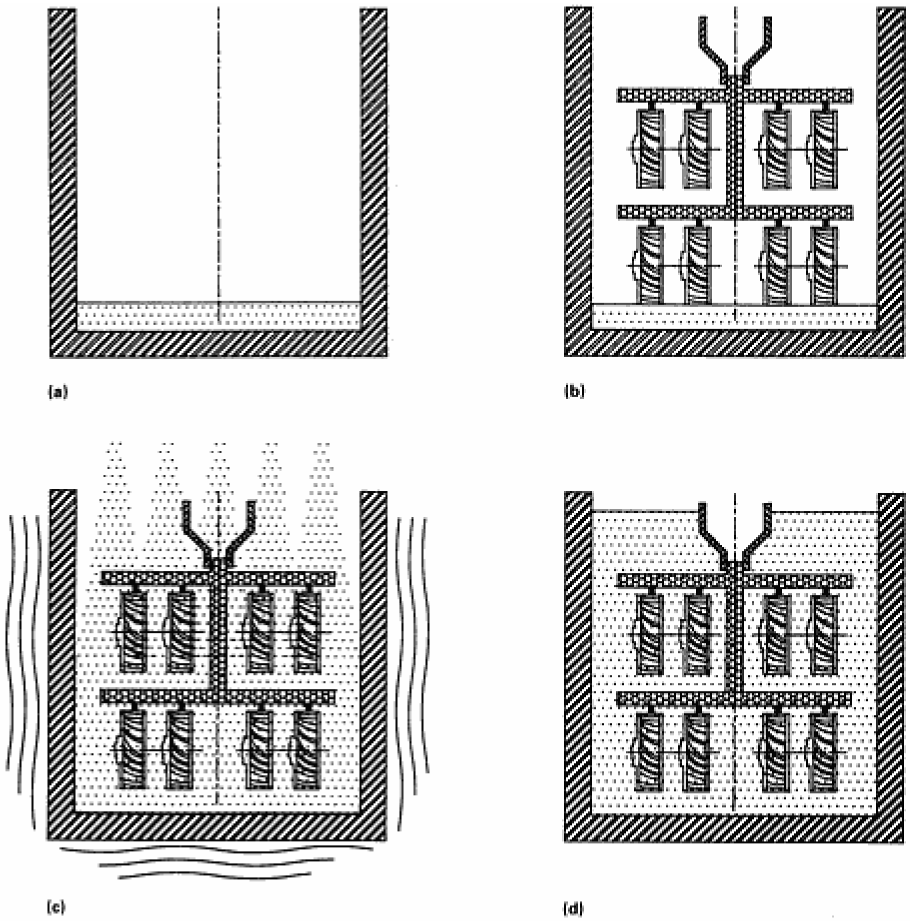


Fig. 9 Lost foam pattern system. (a) Flask that contains a 25 to 75 mm (1 to 3 in.) sand base. (b) Positioning the pattern. (c) Flask being filled with sand, which is subsequently vibratory compacted. (d) Final compact ready for pouring

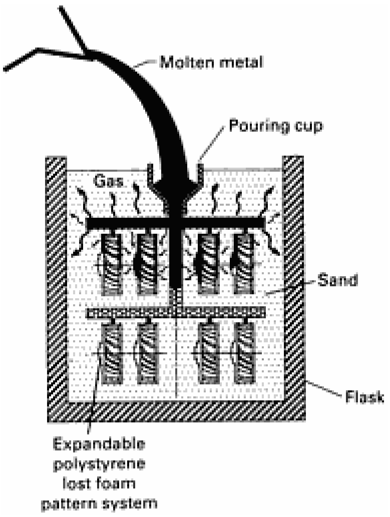

Molten metal
Pouring cup
Gas
Sand
Flask
Expandable polystyrene lost foam pattern system

Fig. 10 Pouring of a lost foam casting

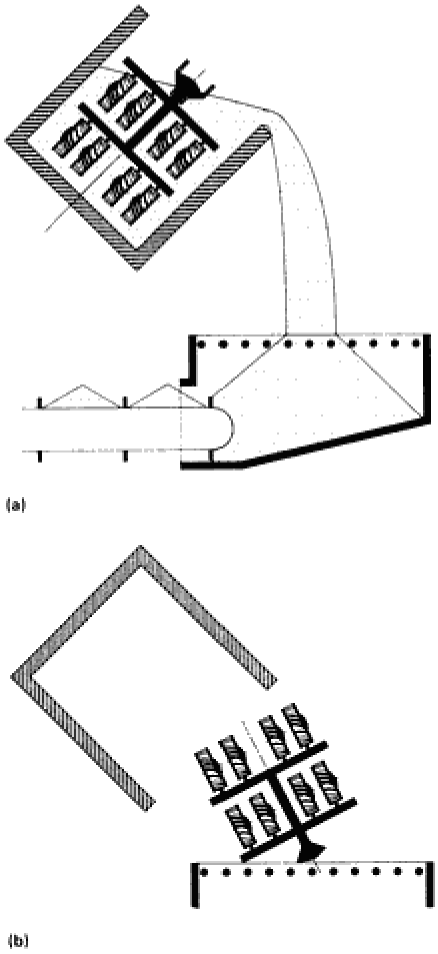


Fig. 11 Processing of completed (cooled) casting. (a) Flask is tipped, and the sand is recycled. (b) Casting is ready for degating and cleaning

Pattern Molding, Assembly, and Coating. The first step in the process is to produce the pattern. The pattern material is supplied as small beads of polystyrene or a mixture of polystyrene and other foamed plastics, such as polymethylmethacralate. The beads are pre-expanded using heat to about forty times their original volume. The expanded beads are cooled and held for a period of time to stabilize their dimensions.

The molding process consists of four steps: filling the die, fusing the beads, cooling the pattern, and ejection. During filling, the beads are fed into the die. After the mold cavity is full, the beads are heated by steam that travels through the mold. With exposure to the steam, the beads expand again and fuse together. The die is then cooled to stop the expansion process, and the patterns are ejected from the die. After the pattern is removed from the die, it will shrink slightly over the next 24 h. Because shrinkage is not necessarily uniform, the pattern producer must compensate for pattern shrinkage in designing the pattern die.

After the 24 h holding period, the patterns are assembled. Complex shapes may be made by producing partial patterns and gluing them together. Gates and risers are attached and glued on to the patterns to make an assembly. Usually one assembly is used in each flask.

The pattern assembly is coated with a refractory slurry. The use of the slurry gives the finished casting a smoother surface and controls the escape of pattern decomposition products, such as gases, from the burning pattern material. In lower melting point metals, the patterns do not burn, but they do form liquid decomposition products, which must also escape through the coating. The choice and application of the proper coating is crucial to the success of the lost foam process, because permeability of the coating controls the rate of escape of these decomposition products, which in turn controls the pouring process. Coatings are often custom blended for a foundry and a specific part. The coating is usually applied by automated pattern dipping machines, which control coating thickness more uniformly than hand application. Coating refractories are selected based on the metal being poured and the permeability desired. The carrier used in the slurry is usually water, because organic solvents attack the pattern material. The coating is dried thoroughly before the pattern is invested with sand. This process can be done at room temperature, which usually takes 24 h, or using heated forced air at 50 to 65 °C (120 to 150 °F), which reduces the drying time to less than 6 h.

Investing the Foam Pattern in Sand. The pattern is placed on a bed of sand in the flask, and loose, dry sand is introduced into the flask through a sand raining system. During filling, the flask is vibrated to pack the sand uniformly around the pattern. The sand may be silica sand; however, the use of uniform spheres of mullite or other refractories is also possible. The spherical shape aids in packing, and, because mullite has a lower coefficient of expansion than silica, more accurate castings are obtained. A vacuum may be applied to the flask during pouring. This not only removes any gases generated during pattern decomposition, but it makes the mold more rigid.

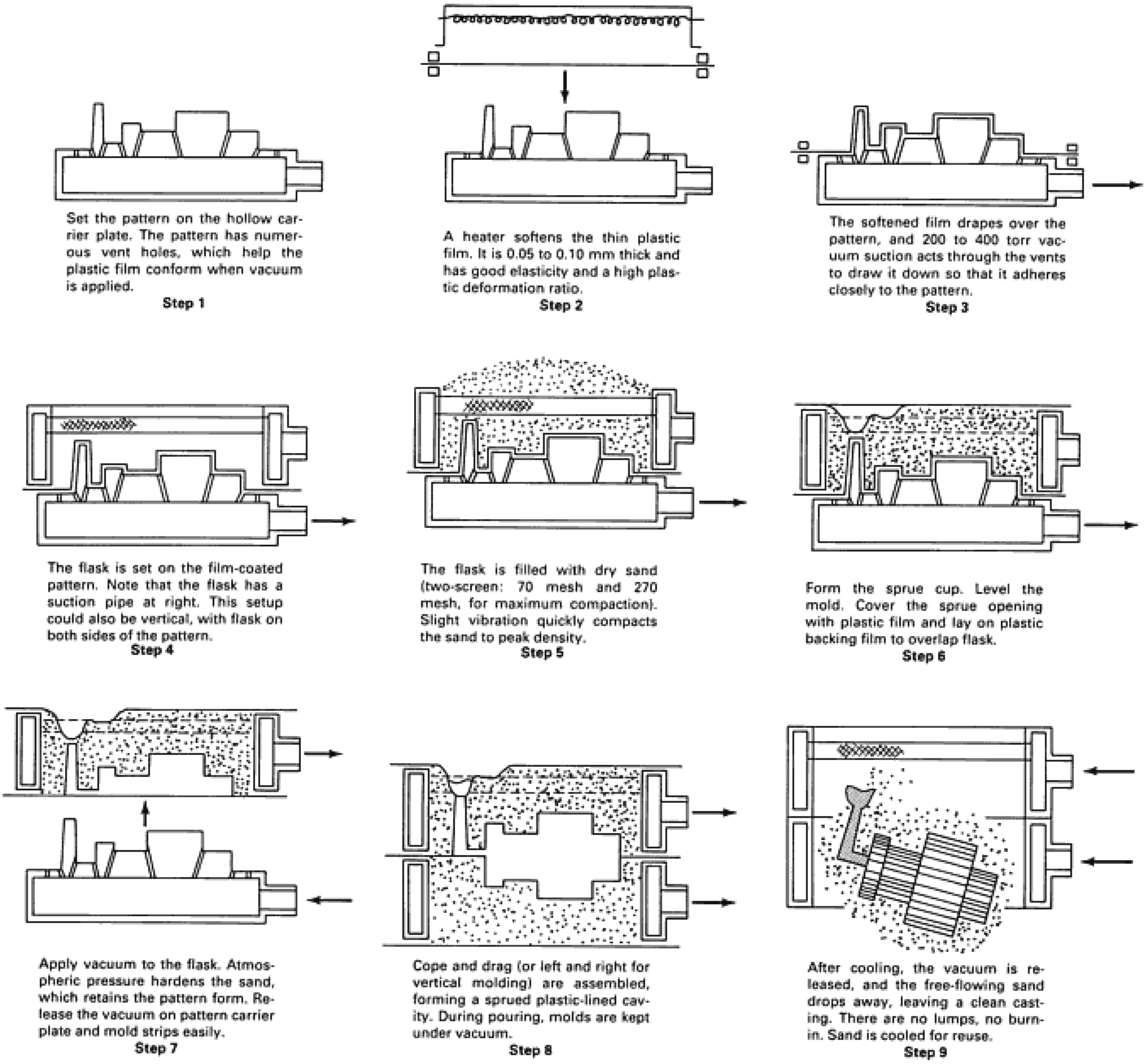
Pouring Practice. Castings are poured using the same techniques used in pouring bonded sand castings. In one variant of the process, the gases that escape from the mold during pouring are burned by torches above the mold. This effect creates a vacuum within the mold that increases its rigidity. After pouring, the castings are cooled, dumped out of the flask, and processed normally. The sand may be thermally reclaimed to remove all pattern decomposition products and is cooled before being reused.

Ferrous and nonferrous alloys may be used in this process. Finished castings often reproduce the surface of the foam pattern. Care must be taken in gating lost foam parts to be certain that the molten metal flows through the pattern in one direction. In addition, streams of metal should not meet in the casting itself, because liquid decomposition products are carried on the surface of the leading edge of the metal streams and can become trapped in the casting where the streams meet. The process has had wide acceptance in the automotive industry and has grown steadily in popularity since the late 1980s.

Vacuum Molding (V-Process)

In this binderless process, the sand is positioned between two sheets of thin plastic and held in place during pouring by application of a vacuum. This molding method is especially useful in making large flat castings, such as sounding boards for pianos.

Figure 12 shows the steps in the V-process. The pattern, which contains a number of small vent holes, is mounted on a carrier plate. A thin plastic film is heated and stretched over the pattern, and a vacuum is applied to the pattern, which draws the plastic over the pattern and holds it tightly against the pattern. Because the plastic is softened by the heat, it conforms to the surface of the pattern. A specially constructed hollow-wall flask containing a vacuum connection is placed around the pattern, filled with sand, and vibrated to compact it. A sheet of plastic is placed over the top of the mold, and a moderate vacuum is applied to the flask. The vacuum holds the sand tightly in place, producing a dense, strong mold. The vacuum is released on the pattern, which is easily removed from the mold.



Set the pattern on the hollow carrier plate. The pattern has numerous vent holes, which help the plastic film conform when vacuum is applied.
Step 1

A heater softens the thin plastic film. It is 0.05 to 0.10 mm thick and has good elasticity and a high plastic deformation ratio.
Step 2

The softened film drapes over the pattern, and 200 to 400 torr vacuum suction acts through the vents to draw it down so that it adheres closely to the pattern.
Step 3

The flask is set on the film-coated pattern. Note that the flask has a suction pipe at right. This setup could also be vertical, with flask on both sides of the pattern.
Step 4

The flask is filled with dry sand (two-screen: 70 mesh and 270 mesh, for maximum compaction). Slight vibration quickly compacts the sand to peak density.
Step 5

Form the sprue cup. Level the mold. Cover the sprue opening with plastic film and lay on plastic backing film to overlap flask.
Step 6

Apply vacuum to the flask. Atmospheric pressure hardens the sand, which retains the pattern form. Release the vacuum on pattern carrier plate and mold strips easily.
Step 7

Cope and drag (or left and right for vertical molding) are assembled, forming a sprued plastic-lined cavity. During pouring, molds are kept under vacuum.
Step 8

After cooling, the vacuum is released, and the free-flowing sand drops away, leaving a clean casting. There are no lumps, no burn-in. Sand is cooled for reuse.
Step 9

Fig. 12 Elementary sequences in producing V-process molds

Cope and drag halves of the mold are assembled while maintaining the vacuum, and the casting is poured. After the casting cools, the vacuum is released, and the loose sand falls away from the casting. Before pouring, the plastic that covers portions of the mold cavity normally open to the atmosphere (such as the tops of risers, vents, and the pouring sprue) is removed so that the casting cavity remains at atmospheric pressure during pouring. If it did not, the mold would collapse. Gases generated during pouring must escape to the atmosphere, not into the mold where they would destroy the vacuum.

The V-process is not normally used for high production runs; however, molding lines have been built that permit a production rate of 60 molds per hour. As the plastic film vaporizes during pouring forming, it forms a reducing gas that prevents the formation of an oxide skin on the molten metal; hence, metal fluidity is often improved. However, as the molds contain no moisture, the initial cooling rate in the mold is slower.

Ceramic Molds

IN CERAMIC MOLDING, a fine refractory aggregate is combined with a silicate binder. The resulting castings usually have very fine surface finish and very accurate dimensions.

Investment Casting

In investment casting, also called the "lost wax" process, a ceramic slurry is applied around a pattern, usually made of wax, and hardened to make a mold. The pattern is removed, usually by heat, and molten alloy is poured into the space formerly occupied by the pattern. There are two forms of investment casting. One possibility is that the ceramic mixture is poured around the wax in a flask and allowed to harden (the "solid mold" process). The other method occurs when the pattern is repeatedly dipped in a ceramic slurry, dusted with refractory, and dried in a repetitive process until a shell of sufficient thickness has been formed around the pattern. Today, the solid mold process is used primarily for jewelry and dental casting; the overwhelming majority of investment castings are made using the ceramic shell process, which is shown in Fig. 13.

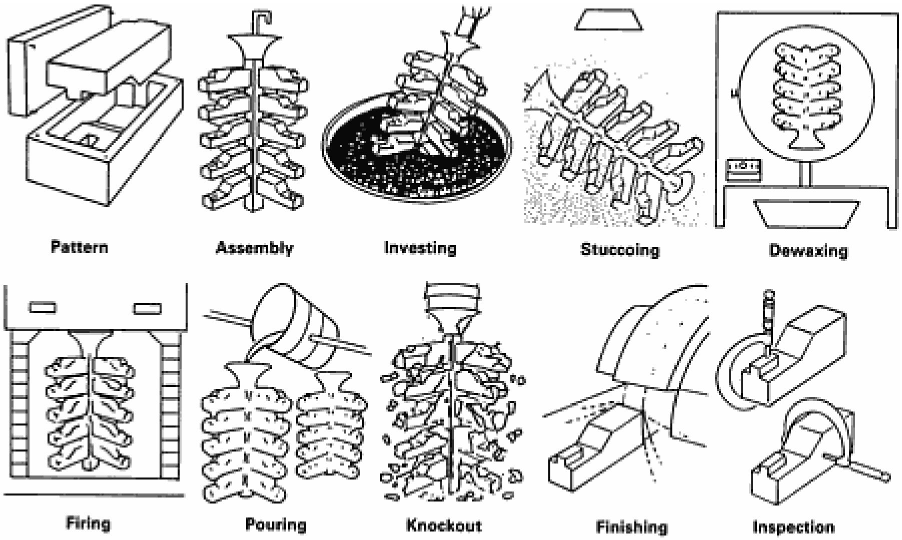


Fig. 13 Steps in the investment casting process

Patterns. The pattern is formed by injecting pattern wax into a pattern die. Pattern wax is a blend of natural wax modified with fillers, resins, plastics, plasticizers, antioxidants, and dyes. Waxes used for patterns are most often paraffins, vegetable waxes, and microcrystalline waxes. By blending these waxes with each other and adding modifiers as needed, waxes having very specific properties can be produced. The choice of what kind of wax to use depends on the size and shape of the casting to be produced. Additives are used to increase the strength of the wax and to compensate for its shrinkage on cooling.

Cores. Preformed ceramic cores are placed in the pattern die before injection. Alternatively, soluble wax cores may be used instead of ceramic cores; these are dissolved out of the pattern using a weak acid before the slurry is applied. The preformed ceramic cores are primarily made of silica and alumina; they are removed from the casting by dissolving the cores in a caustic solution after casting. The cores are made by injecting the core mixture (usually a slurry of finely divided refractory aggregate in ethyl silicate) into a die. The cores gel in the die and are removed and fired to develop the strength they need to withstand wax injection and metal pouring pressures. They may be very complex, as shown in Fig. 14.

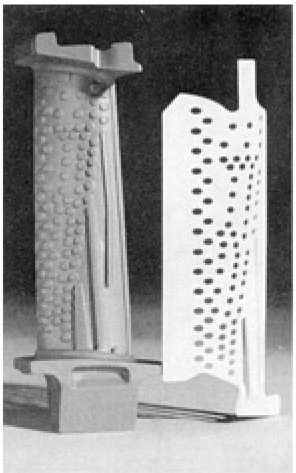


Fig. 14 Investment cast turbine blade with convex wall removed showing complex core

Pattern Injection and Assembly. The patterns are injected at moderately low temperatures and pressures. After they harden in the die (which usually occurs in less than a minute for small parts), they are removed from the die and allowed to cool. If they contain preformed cores, they may be x-rayed to be sure that the cores did not fracture during injection. The patterns are inspected visually, die parting lines and the injection feeder are removed, and surface blemishes repaired. The patterns are then attached to a wax downsprue by melting the joint area and holding the pattern against the sprue until the joint hardens. The assembled clusters are inspected and cleaned by dipping in a solution containing a mild solvent that etches the surface of the pattern so that the slurry adheres to it.

Manufacture of Ceramic Shell Molds. The pattern assembly is then dipped into the first of a series of ceramic slurries. The slurries are usually mixtures of refractory aggregate in an aqueous silica sol (colloidal silica). Because of health concerns, ethyl silicate is rarely used as the binder. In addition to the colloidal silica and the aggregate, the slurry may contain a wetting agent, bactericides, antifoaming compounds, and polymers, which are added to give the slurry sufficient green strength, so that it can be re-dipped without being completely dried between dips. Slurry formulations are usually proprietary. The colloidal silica is a colloidal dispersion of virtually spherical particles of silica in water. The average particle size is 7 to 10 nm. Slurries are controlled by adjusting viscosity, temperature, and solids content.

The first slurry consists of a fine refractory aggregate, usually more expensive than that used in later dips. This aggregate contacts the molten metal. The pattern cluster is rotated in the dip tank to coat all pattern surfaces. Automated dipping machines assure repeatability of the dipping process. The wet cluster is then coated with refractory aggregate, which adheres to the slurry. The cluster is dried in ambient air, or heated forced air may be used to accelerate the drying process. A second slurry coat is then applied. Its composition will often be similar to that of the first slurry. However, the refractory sand that is applied in this coat is usually more coarse and less expensive than that applied to the first coat. The cluster is dried again, and the process is repeated; this time using a coarser, less expensive refractory in the slurry and sanding operations. After about seven applications of slurry and refractory sand, the mold is given a final drying and prepared for the dewaxing operation.

Pattern Removal. The patterns are usually removed by melting or burning them out of the mold. However, because the pattern material expands about 40 times as much as the mold, care must be taken to avoid cracking the mold during this operation. Wax drain holes are often added to the cluster to provide a path for molten wax to escape during the dewaxing operation. Wax is a poor conductor of heat, so the outer layers of the pattern melt and run out of the mold before the inner parts of the pattern heat enough to expand to crack the mold. One method of dewaxing is to use a steam autoclave. In this method, superheated steam is introduced to the patterns at a pressure of 550 to 620 kPa (80 to 90 psig). The steam penetrates the porous mold and gives up its latent heat of vaporization on the wax surface, which heats the surface very rapidly and causes the part of the wax in contact with the steam to melt. As that wax runs out of the mold, it exposes the wax underneath to the steam, which melts it, and the process continues in this manner. The wax runs into a trough below the molds and can be recovered and reprocessed.

An alternate method of dewaxing is to flash fire the molds. In this process, the molds are placed in a furnace at 870 to 1095 °C (1600 to 2000 °F). The heat melts and burns out the wax. Wax that is not burned falls into a trough below the furnace and can be reclaimed. Flash dewaxing units are equipped with afterburners to eliminate smoke emissions.

Mold Firing. After dewaxing, the molds are fired at 870 to 1095 °C (1600 to 2000 °F) to remove any residual pattern material, completely dry the molds, and sinter the mold ceramic so that it develops the strength it needs during pouring. This operation may be combined with wax removal in flash dewaxing furnaces and with mold preheating prior to pouring. Investment casting molds are usually preheated prior to pouring to promote complete metal fill in the thin sections typical of investment castings, and to lessen the thermal shock on the molds when they are filled with molten metal.

Mold Preheating Prior to Pouring. To control solidification, the molds may be wrapped in refractory blankets prior to preheating. The preheat temperature is determined by the alloy being poured and the casting geometry. When the molds are completely preheated, they are filled with molten metal. Because the amount of metal poured in investment castings is usually small (<20 kg, or 45 lb), the molds may be poured by hand, or they may be clamped to a furnace just large enough to melt the metal for a single mold. As soon as the metal reaches the pouring temperature, the furnace and mold are rapidly inverted, which fills the mold in a smooth even manner.

Melting and Casting. Melting is usually done using prealloyed charges prepared by a custom alloy producer. For some alloys, notably superalloys and titanium alloys, melting, pouring, and solidification is carried out in a vacuum (approximately 10^{-3} torr) to protect the alloys from reactions with oxygen. Induction melting is most often used, although gas-fired furnaces may be used for nonferrous alloys, and vacuum-arc remelting is often used for titanium and refractory metal alloys. In dental and jewelry castings, the molds are often centrifuged during pouring to assure fill of the intricate designs.

Postcasting Operations. After casting, the molds cool, and the ceramic is removed. Clusters are shot blasted, and the casting cut from the sprue. Finishing and inspection operations are similar to those used for sand castings; except, if preformed ceramic cores are used, they must be removed in a caustic bath. If the cores have especially small cross sections, they may be removed in a caustic autoclave, which is pulsed periodically to remove the reaction layer at the core-caustic interface. Caustic (potassium hydroxide) is used to dissolve the silicate binder in the core, allowing the core aggregate material, usually silica and alumina, or an aluminosilicate, to fall out of the casting.

Plaster Casting

Plaster molds are used to produce nonferrous castings having smoother as-cast surfaces (50 to 125 rms), better dimensional accuracy, and thinner sections than can be produced using sand casting techniques. The plaster casting process is used to produce near-net shape castings such as impellers, tire molds, matchplate patterns for foundries, and electronic equipment housings.

Plaster Mold Compositions. In the conventional plaster mold process, the principal mold ingredient is calcium sulfate. Other materials may be used to enhance mold properties, such as green strength and permeability. These materials include cement, talc, fiberglass, sand, clay, and other materials. Calcium sulfate exists as two different hydrates and in an anhydrous form. Its dihydrate is known as gypsum ($CaSO_42H_2O$). Above 128 °C (262 °F), gypsum loses three-fourths of its water to become plaster of paris, which loses the rest of its water at 163 °C (325 °F) to become calcium sulfate.

Mold Production. To produce a plaster mold, plaster of paris is mixed with water to form a slurry, which is immediately poured over a pattern or into a core box, where it sets, forming a solid mold or core of gypsum with free water distributed in the mold. The pattern is normally coated with a release agent before the slurry is poured. Mechanical vibration may be used to eliminate pinholes in the mold while the slurry is being poured over the pattern. The mold is then dried at temperatures high enough to produce calcium sulfate and to burn out any residual pattern materials (such as wax) that may have been used. Drying must be carried out at a temperature high enough to remove all moisture but not so high that the molds crack. Patterns and core boxes are usually made of aluminum. However, flexible rubber or urethane patterns may be used to produce molds having negative draft or very complex sections.

Metals Cast. Plaster molds have low heat capacity, which means metal flows well in them to fill thin sections, but solidification rates are low. For mushy freezing alloys, this means that, because cooling rates are low, properties will generally be lower than those in castings made in sand molds. Plaster molds also have low permeability, so vacuum or pressure assists are often used to help fill thin sections. Aluminum-, copper- and zinc-base alloys may be poured in plaster, but magnesium alloys generally are not because of the possibility of a violent reaction between the molten magnesium and any free water in the mold. Ferrous metals are not poured in plaster molds because the iron reacts with the sulfate to produce very poor surfaces.

The Antioch Process. A variation on plaster molding is the Antioch process. In this process, after the molds have set, they are stripped from the pattern and steam autoclaved for 8 to 10 h at a pressure of two atmospheres (205 kPa, or 30 psi). During this time, partial dehydration occurs and recrystallization produces a granular structure in the mold having improved permeability. The molds are then dipped in water and allowed to stand for 10 to 14 h to complete the granulation reaction. Molds must then be oven dried to remove the combined and excess water.

Foamed Plaster Molding Process. Another variation, which produces molds having higher permeability than Antioch process molds, is the foamed plaster process. In this process, a foaming agent, such as alkylaryl sulfonate, is added to either the dry ingredients or the liquid slurry. A special mixing method (using a specially-designed mixing disk) foams the slurry with many fine air bubbles, which decreases the density and increases the volume of the slurry. The molds have smooth surfaces, with air bubbles just below the surface. Air bubble size must be controlled so that all bubbles are about 0.25 mm (0.01 in.) in diameter, because larger bubbles break under pressure from the molten metal, forming surface defects on the casting surface. During setting and drying, these air cells become interconnected, thus permitting the escape of gases when metal is poured into the mold. The permeability of the mold depends on the volume increase that results from the addition of air when the slurry is mixed.

Other Ceramic Molding Processes

A number of ceramic molding methods are based on proprietary processes that use permanent patterns and fine-grain zircon and calcined high-alumina mullite slurries for molding. They are used primarily to produce forging and extrusion tools and dies; food service equipment; glass molds; valves for the food processing, chemical, and pharmaceutical industries; and marine hardware. Dimensional control and surface finish are similar to that of investment castings, but the size and weight of castings made in ceramic molds is generally greater than those made as investment castings.

The Shaw process is actually two processes. One process consists of a mold with a monolithic structure produced from a slurry having a fine aggregate. In the second, the mold is a composite. The fine aggregate slurry is used only to form the mold/metal interface; it is backed with a less expensive coarser slurry. The first process is used for small parts and has generally been supplanted by investment casting, while the second process is used for larger castings.

The heart of these ceramic molding processes is the binder, which is prehydrolyzed ethyl silicate. Ethyl silicate is produced by reacting silicon tetrachloride with ethanol to form tetraethylorthosilicate, $Si(OC_2H_5)_4$. The use of condensation-polymerization treatments decreases the water content and raises the silica content; commercial binders usually contain 40% silica. The binder forms a gel during mold making, which provides green strength for the mold. The gel is formed either by evaporation of water, which is fairly rapid, or by changing the pH of the gel. Maximum stability of the binder (longest gel time) is found at a pH of 1.5 to 2, while the shortest gel time is achieved with a pH of 5 to 6. Thus gelling can be accelerated by starting with a binder having a low pH during pattern coating and mold building and then raising the pH when it is time to gel the slurry.

Two sets of patterns are used, an oversize preform pattern for molding the coarse backup material, and the finish pattern, which produces the final mold cavity. The preform pattern is about 2.5 to 10 mm (0.1 to 0.4 in.) oversize. The backup refractory and binder are mixed to the desired consistency, rammed or vibrated over the preform pattern, and gelled by gassing with carbon dioxide. The backup mold aggregate is usually a coarse-grained low-cost refractory, such as an aluminous fireclay, and the backup binder is usually sodium silicate.

The ceramic facing is usually made using fine zircon, alumina, or mullite flour, mixed with hydrolyzed ethyl silicate and often a gelling agent. The slurry is poured over the pattern through pouring gates in the backup mold. The slurry may be degassed in a vacuum chamber before pouring to remove any air bubbles. It gels within a few minutes after pouring, forming a rubber-like consistency, which permits patterns having no draft to be stripped successfully. After the mold is stripped, it is ready for stabilization. In the Shaw process, stabilization is accomplished by burning the alcohol off with a torch. During burning, microcraze cracks form in the mold, which enhances its permeability and facilitates shakeout. The mold is then baked to remove all remaining volatiles. Molds may be preheated for pouring or poured at room temperature.

The Unicast process differs from the Shaw process principally in the method of mold stabilization. In the Unicast process, the ethyl silicate mold is stabilized by immersing in a liquid before burn-off. The liquid may be boiling water, or other organic liquids, such as kerosene or acetone. Using a liquid stabilization process reduces any warping of the mold that might occur as a result of the thermal gradients established during torch firing. Another difference between the Unicast and Shaw processes relates to the sequence followed in preparing composite molds. In the Shaw process, preparation of the coarse mold backup precedes pouring of the fine ceramic facing; in the Unicast process this sequence is reversed.

Other ceramic molds may be made by bonding the refractory aggregate with calcium or ammonium phosphate. These molds are made by a dry pressing method in which the molding mixture containing 4 to 9% moisture is pressed in dies at pressures of 14 to 140 MPa (1 to 10 tsi). After pressing, molds are stripped and fired at temperatures between 900 and 1300 °C (1650 to 2400 °F).

Metallic Molds

METALS may also be used as a molding material. Usually, ferrous metals are used as dies or molds for lower melting point aluminum-, magnesium-, zinc-, and copper-base alloys. However, steel has been successfully poured into water-cooled aluminum dies. In the United States, when metal is poured by gravity into metal molds, the process is called "permanent molding"; in the rest of the world, this process is known as "gravity die casting." When high pressure is used to fill the mold cavity, the term used in the United States is "die casting"; elsewhere it is "pressure die casting." United States terminology will be used in this section.

Permanent Molding

In permanent mold casting, the mold is made of metal and is reusable. The process is especially useful for high volume production of fairly simple shapes; however, the use of sand cores ("semipermanent molding") makes possible the production of complex castings, such as automobile cylinder heads.

Mold Design. The mold material used most often is cast iron, which machines easily and resists oxidation. For very high production runs, tool steels or low-carbon steel tools may be used. The molds often contain internal cooling passages through which water flows to remove heat from the die, and the dies are usually coated with a ceramic slurry between pours. Because metal molds extract heat more rapidly from solidifying castings, the cast structure (grain size) of permanent mold castings is generally finer, and castings have less microporosity than sand castings. Casting dimensional reproducibility and surface finish is generally excellent, which often allows many machining operations to be eliminated. Multiple-cavity dies may be used to increase productivity. These advantages outweigh the higher cost of the permanent mold tooling. Aluminum-, magnesium-, zinc-, and copper-base alloys and small cast iron parts may be made in permanent molds.

Figure 15 shows a simple book-type permanent mold. In operation, the operator applies a thin layer of ceramic mold coating to the surface of the mold, closes the mold, clamps it shut, pours in the metal, waits for it to solidify, and then opens the mold and removes the casting, cleans the mold of flash and excess coating, and then repeats the process. The mold is not allowed to cool to room temperature between pours. The first few pours on the mold each day are made to heat the mold, and castings made from these pours are generally scrapped. To minimize the number of castings that are scrapped, molds are normally preheated electrically or using gas torches before casting operations begin.

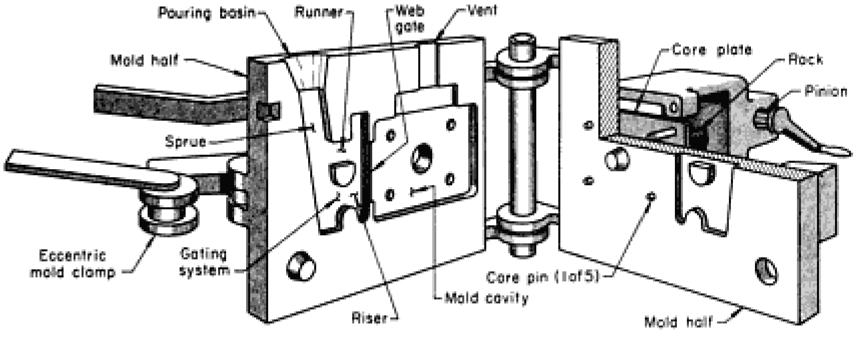


Fig. 15 Book-type manually operated permanent mold casting machine, used principally with molds having

shallow cavities

Permanent molding is easily automated (Fig. 16, 17). Pouring may be automated using tilting pour ladles, or the mold may be placed in a cradle. As the metal is poured into the mold, the cradle is lowered at a rate consistent with the desired rate of fill, effectively filling the mold at a constant level. If the metal source, rather than the mold, is in the cradle, it is raised, and the mold remains stationary. This method virtually ensures controlled fill and the elimination of turbulence and dross entrapment in the casting. Another method used to fill large permanent molds is to fill reservoirs at one end of the mold with metal, and then tilt or rotate the mold so that the metal runs smoothly through the mold, filling it in a uniform and consistent manner.

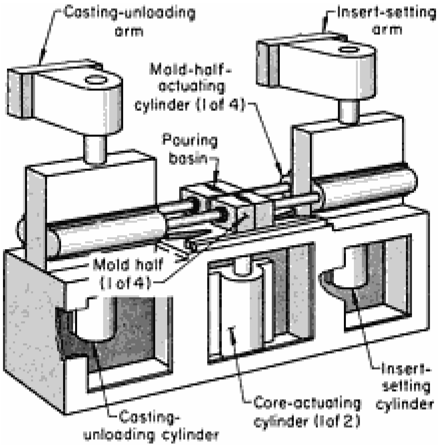

Casting-unloading arm
Insert-setting arm
Mold-half-actuating cylinder (1 of 4)
Pouring basin
Mold half (1 of 4)
Insert-setting cylinder
Casting-unloading cylinder
Core-actuating cylinder (1 of 2)

Fig. 16 Automatic permanent mold casting machine with a setter for cast-in inserts

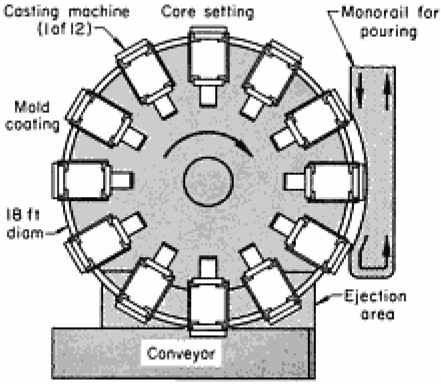

Casting machine (1 of 12)
Core setting
Monorail for pouring
Mold coating
18 ft diam
Ejection area
Conveyor

Fig. 17 Schematic of a 12-machine turntable for automatic permanent mold casting

Tool life is a major consideration in permanent molding. The most common cause of tool failure is heat checking, small cracks in the surface of the tool, which produce ridges in the casting and eventually lead to failure of the tool. Heat checking is caused by thermal fatigue of the mold. Thermal fatigue involves repeated heating and cooling of the mold during the casting production run. Factors that influence mold life are those that affect thermal fatigue, either by increasing the temperature difference between areas of the mold or by increasing the stresses these temperature differences cause. These factors include alloy pouring temperature (higher temperatures increase thermal fatigue), casting weight and shape (heavy sections contain more heat than thin sections), cooling methods (the proper placement of cooling lines is essential to minimize heat checking), and mold coatings. These factors control the temperature of the mold. Note that the mold temperature will probably not be uniform over all surfaces of the mold; minimizing this difference can substantially increase mold life.

Mold design also plays an important role in mold life and casting quality. Variation in mold wall thickness causes excessive stress to develop during heating and cooling, which in turn causes premature mold failure from cracking. Abrupt changes in thickness without generous fillets also cause premature mold failure. Small fillets and radii concentrate stresses, again decreasing mold life.

Mold coatings are used to prevent premature freezing of the metal in the mold, to control the rate and direction of casting solidification, to minimize thermal shock to the mold, and to prevent reactions between the metal being poured and the metal mold (aluminum alloys, in particular, tend to solder to ferrous dies). Coatings must be inert to the metal being cast, noncorrosive to the metal mold material, and adhere to the mold. A primer coat may be applied to the mold first. Coatings are usually sprayed on the mold. They may be brushed on by hand, but this is a slower process, and does not produce as uniform a coating as spraying. Coatings are usually thin water-based slurries of mixtures of refractory particles; the high temperature of the mold evaporates the moisture in the coating before pouring takes place. Coating thickness must be controlled to maintain casting dimensions, and it is usually thicker on gates and risers. Coatings are not always applied after each cycle, but they must be refreshed periodically through the production run. The choice of coating composition is usually dictated by the alloy being cast.

Casting Quality. As in other casting methods, the quality of the casting depends on the gating and risering system. However, in permanent molding, the fact that the mold is heated as a result of the process also affects casting quality. The placement of cooling lines or flame heated "anti-chills" to maintain the proper thermal gradient in the mold is often necessary to assure quality castings. Rapid cycle times allow less time between pours for the mold to cool, and thus the mold temperature increases.

Low-Pressure and Vacuum Permanent Molding. In low-pressure permanent molding, the mold is placed in a casting device above a sealed airtight chamber that contains a crucible holding molten metal. A fill tube extends from the mold down into the metal bath, and the casting is made by pressurizing the chamber and forcing metal up the fill tube into the casting. This process usually operates at lower mold temperatures and shorter cycle times than conventional permanent molding, and the advantages of counter-gravity mold filling listed in the article "Solidification of Metals and Alloys" apply here. Vacuum casting is similar, except that a vacuum is created in the mold cavity and the metal is pulled rather than pushed into the mold cavity. These processes are compared schematically in Fig. 18.

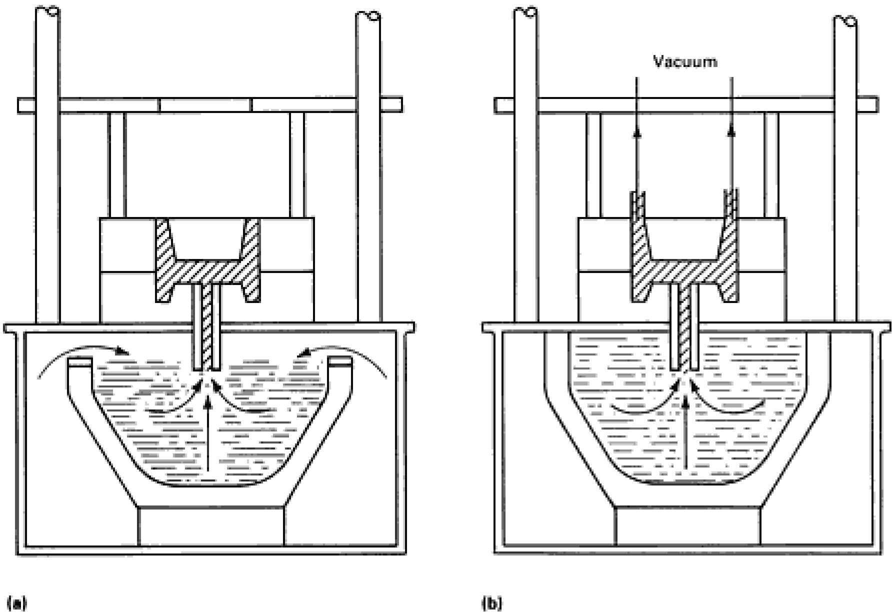


Fig. 18 Schematics of low-pressure (a) and vacuum casting (b) units used with permanent molds

Graphite Molds. Permanent molds can be machined from solid blocks of graphite instead of steel. The low coefficient of thermal expansion and superior resistance to distortion of graphite make it attractive for the reproducible production of successive castings made in the same mold. Because graphite oxidizes above 400 °C (750 °F), graphite molds are usually coated with a silica wash. These molds are usually used to make bronze bushings or cast iron railroad wheels. Because gravity pouring of molten iron erodes the graphite molds, counter-gravity mold filling is used.

Die Casting

In pressure die casting, the metal is injected into the mold at high pressures. The process is primarily used for high-volume production of zinc, aluminum, and magnesium alloys, although ferrous and copper-base alloys may also be cast. The process is capable of high production rates. Production rates are related to the size and complexity of the part. Parts as complex as automotive engine blocks and transmission housings are routinely made by die casting.

Die Casting Processes. There are two major types of die casting machines: hot chamber and cold chamber. In the hot chamber machine (Fig. 19), the injection chamber is a gooseneck inserted in the melt. Pressure is applied to the melt to force some of the metal into the mold. This method avoids one metal transfer operation, and it is used primarily for zinc and magnesium. In the cold chamber process (Fig. 20), the metal is melted separately and poured or metered into the shot sleeve. The piston is then activated to force the metal into the mold. Cold chamber machines are used for aluminum, because the process minimizes the amount of time that the molten alloy is in contact with the die casting machine.

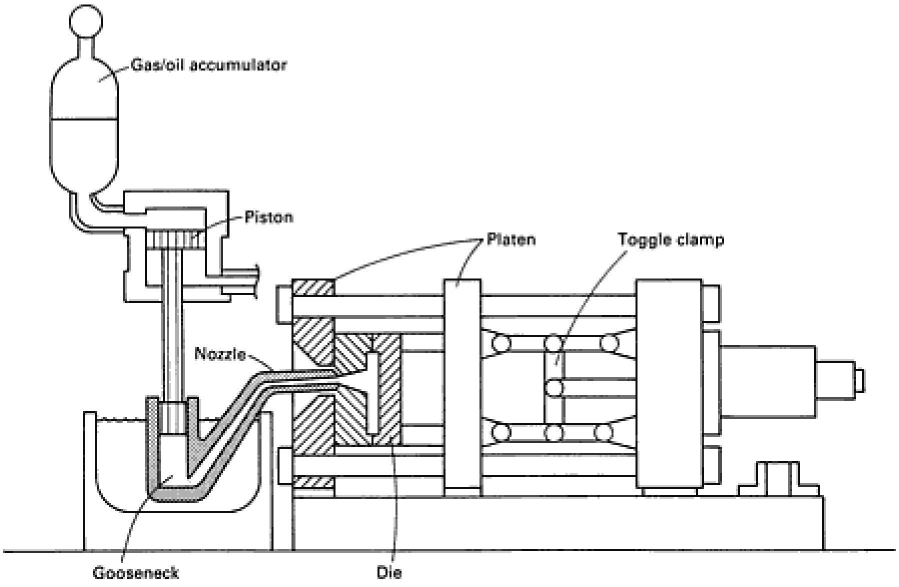


Fig. 19 Schematic showing the principal components of a hot chamber die casting machine

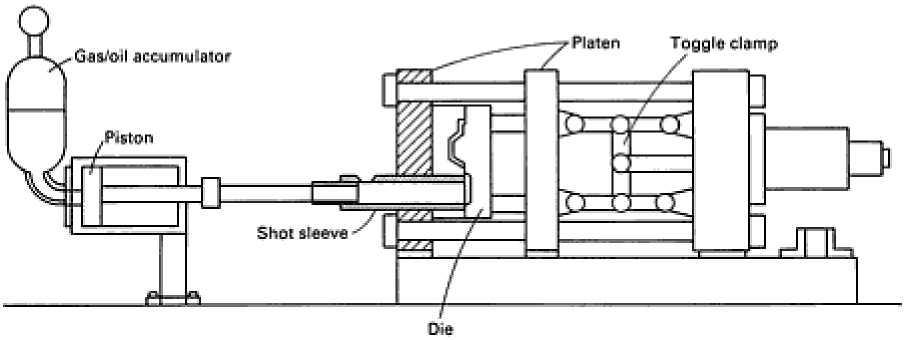


Fig. 20 Schematic showing the principal components of a cold chamber die casting machine

Dies. The die consists of at least two parts, the cover half and the ejector half (Fig. 21). The dies are made of heat-resistant tool steels. The metal enters the die through the nozzle or shot sleeve, which is located in the cover half. The cover half is stationary during casting. Ejector pins, which are activated when the ejector half retracts after the casting is solid, are located in the ejector half of the die. The gating is also generally placed in the ejector half of the die. Undercuts in the casting may be formed by metal slides or retractable cores in the die, which can enter the die space from each side as well as the top and bottom. Ceramic cores may be placed in the die to make configurations that cannot be made any other way; the cores are removed chemically after the casting is solid.

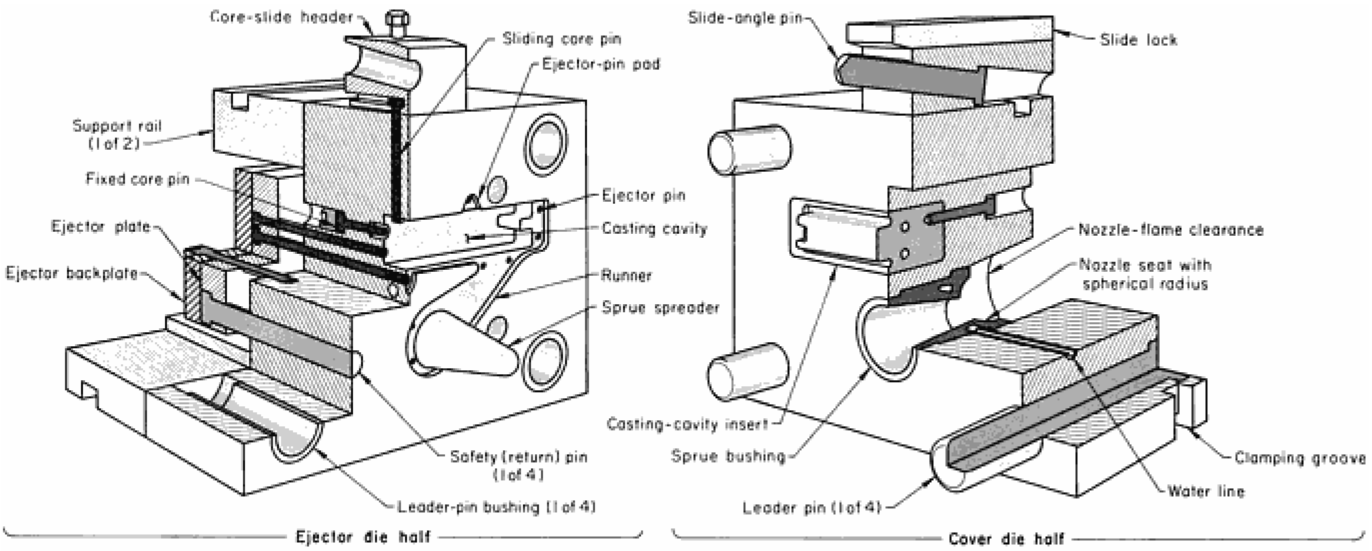

Core-slide header
Sliding core pin
Ejector-pin pad
Support rail (1 of 2)
Fixed core pin
Ejector plate
Ejector backplate
Ejector pin
Casting cavity
Runner
Sprue spreader
Safety (return) pin (1 of 4)
Leader-pin bushing (1 of 4)
Ejector die half
Slide-angle pin
Slide lock
Nozzle-flame clearance
Nozzle seat with spherical radius
Casting-cavity insert
Sprue bushing
Clamping groove
Water line
Leader pin (1 of 4)
Cover die half

Fig. 21 Components of a single-cavity die casting die for use in a hot chamber machine

The die also contains vents and overflow areas where excess metal flows during injection. In addition, most dies contain water cooling lines to control die heating. As in permanent molding, proper placement of the water lines is critical to obtaining good quality castings, especially for multiple-cavity dies.

Processing Sequence. The sequence of the die casting process begins when the die is open before the shot. The die is first sprayed with a lubricant, usually an aqueous solution. This spray coats the die with a thin layer of mold release, and the water evaporates, cooling the die surface. The die is closed, and metal is either injected into the die (hot chamber) or ladled into the shot sleeve (cold chamber). The shot proceeds in three stages. In the first stage, the piston moves slowly, to fill the shot sleeve so that air is not entrapped in the metal before injection begins. In the second stage, the piston moves very quickly, forcing the metal into the mold cavity. The dies are filled in less than 0.15 s. Pressure builds up on the metal during this phase. In the third stage, pressure is intensified to minimize the formation of porosity. The high pressures (up to 70 MPa, or 5 tsi) require elaborate locking mechanisms to keep the dies closed during the cycle; locking forces of up to 45,000 kN (5000 tonf) are used in the largest machines.

After the casting is solid, the dies open, and the casting and its runner system are removed from the die. Slides and cores are usually retracted first, and then the dies open. The gates are trimmed off on a separate trim press. High production die casting operations are highly automated, with the cycle controlled by computer and robots handling the metering of metal into the shot sleeve and removing the casting and gating from the die. After the casting is removed, the die is sprayed again, and the cycle is repeated.

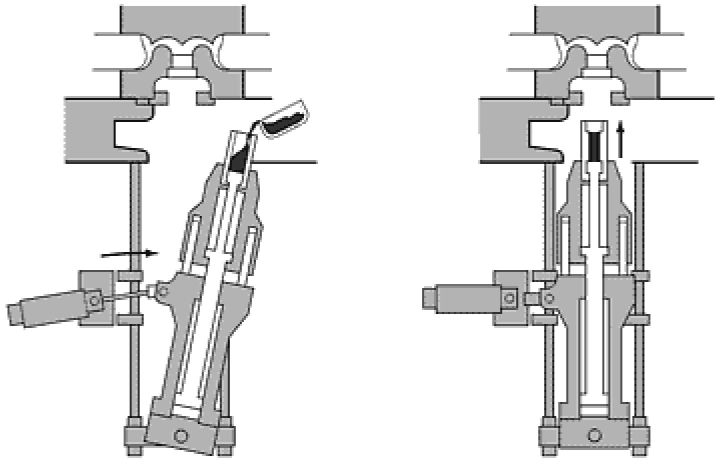
Risers are rarely used in die casting because the metal freezes so quickly that feeding does not have time to occur. The gating system is designed to fill the mold as quickly and efficiently as possible. The area where the shot plunger comes to rest in the gating system is called the "biscuit."

Molten metal may be transferred to the shot sleeve by means of hand ladling, automated ladling, or by being pumped from the melting furnace to the shot sleeve, using pumps made of ceramics, or using electromagnetic force.

Die casting machines are complex. They must be capable of rapid, repetitive motion. The dies must maintain alignment during operation to avoid being damaged, and the cycle of the machine must be controlled accurately. Die failure is usually by thermal shock (heat checking). Iron is often added to aluminum alloys used in die casting to prevent soldering of the alloy to the die. The amount of iron must be controlled, as excess iron (above 0.8%) forms a sludge in the alloy, which, if carried over into the casting as inclusions, will lower casting properties and casting machinability.

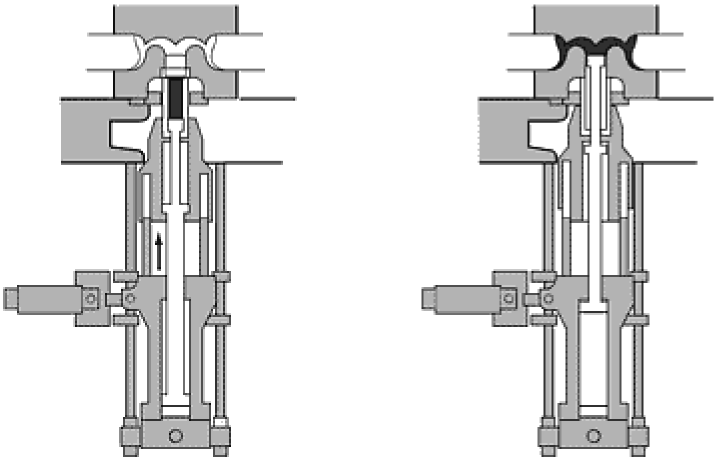
Air Entrapment. The rapid injection of metal into the die cavity inevitably traps air in the casting. This air expands during heat treatment, forming blisters on the surface of the casting. For this reason, most conventional die castings are not heat treated. However, there are a number of methods that may be used to minimize the entrapment of air in the die cavity. In one, the air in the cavity is evacuated prior to making the shot. In another method used for aluminum alloys, the die cavity is filled with oxygen before the shot. During the shot, the oxygen reacts with the aluminum alloy, forming tiny particles of aluminum oxide, which are dispersed in the casting. Because all of the gas in the cavity is used in this reaction, there is no gas to form gas bubbles in the casting.

Because of the limitations of conventional die casting, a variation on the process has been developed to substantially reduce air entrapment. In this method, called "vertical squeeze casting," the shot sleeve is located beneath the die cavity (Fig. 22). The shot sleeve tilts to be filled, then it returns to the injection position. The metal fills the mold at a much slower rate, expelling the gas in the mold ahead of it. Gates are larger than those used in conventional die casting to assure that mold filling is even and free of turbulence, which causes air entrapment. Production rates are slightly lower using vertical squeeze casting, but casting quality is improved. Vertical squeeze casting is not to be confused with another process known as squeeze casting, in which liquid is ladled into the bottom half of a metal die, and the die is closed, similar to a forging press. This process eliminates porosity.



1. Pouring molten metal

2. Shot unit tilts to shot position



3. Sleeve is lifted by docking cylinder and sets into the bottom die

4. Plunger tip goes up to shoot molten metal into the die cavity

Fig. 22 Schematic of the vertical squeeze casting process. Courtesy of UBE Machinery Inc.

Semisolid Casting

Semisolid casting and its variants, known as rheocasting or thixocasting (depending on the amount of solid present at the start of the process), begin the solidification process with the alloy at a temperature between its liquidus and solidus. There is enough coherency in the metal charge that the charge can stand by itself. However, when a force is applied to the semimolten mass, it flows easily and can be injected into a mold cavity. This behavior arises from the unique microstructure of the semisolid mass (Fig. 23). It consists of equiaxed grains formed by stirring the melt during solidification. When the desired solid fraction is obtained, the melt is rapidly solidified to form a billet that can be used in subsequent processing (forging), or the mass is injected into a die cavity. Because the alloy starts its solidification in the mold cavity already partially solid, solidification shrinkage is reduced; so is gas porosity. The process can be operated like injection molding of plastics, with metal charge material fed into a rotating screw cylinder, which heats the metal to the desired fraction solid and delivers it to the die cavity. Nonferrous alloys, most notably aluminum-base alloys, are processed by semisolid casting and forging.

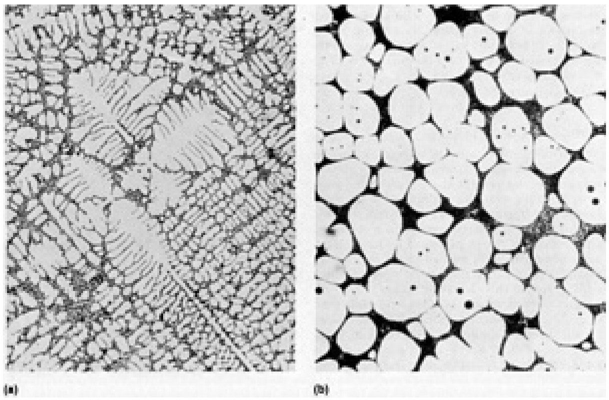


Fig. 23 Comparison of dendritic conventionally cast (a) and nondendritic semisolid formed (b) microstructures of aluminum alloy 357 (Al-7Si-0.5Mg). Both 200×

Centrifugal Casting

When liquid metal is poured into a rotating mold, centrifugal forces throw the metal up against the surface of the spinning mold, and hold it there during solidification. The method may be used when the axis of rotation is horizontal, so that hollow castings having an axis of revolution can be cast without using a core to form the internal surface. The method can also be used when the axis is vertical, in which case the centrifugal force both helps to fill the casting and to force feed metal to the site of solidification shrinkage.

Horizontal centrifugal casting is widely used to make tubes for the petroleum and chemical industry and pipes for municipal water and sewer systems. Figure 24 shows a common design for a horizontal centrifugal casting machine. In operation, the mold is spun up to the desired rotational speed and sprayed with a ceramic coating that acts as the liner for the casting, and insulates the steel mold, decreasing thermal fatigue damage. Molten metal is introduced through a trough at one end. The metal travels down the trough and drops onto the spinning mold surface. The trough is progressively withdrawn from the mold as the mold is filled. After the trough is completely withdrawn from the mold, the casting solidifies. When the casting is solid, it is withdrawn from one end of the mold.

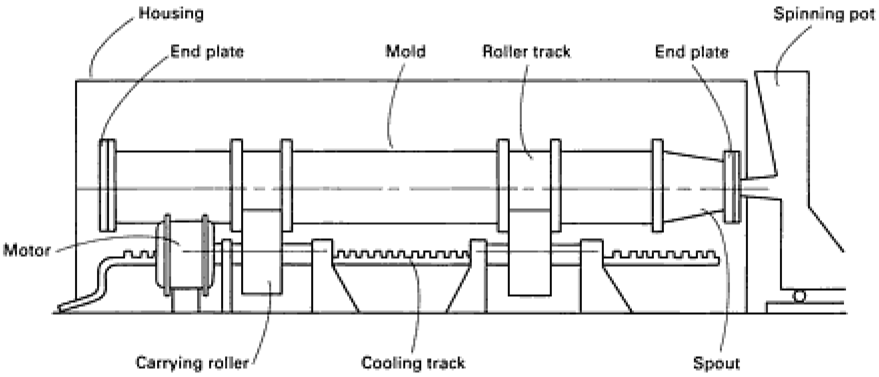


Fig. 24 Schematic of a common design for a horizontal centrifugal casting machine

The mold material is generally steel, although copper or graphite may also be used. A sand core can be placed in one end of the mold. Mold coatings are important for regulating the solidification rate of the metal in the mold. The mold may be cooled during casting by external water sprays. The mold is rotated at a speed that exerts a centrifugal force of 75 to 120 times the force of gravity. The pressure gradient established across the tube thickness causes alloy constituents of various densities to separate. Lighter particles, such as slag and nonmetallic inclusions, gather at the internal diameter of the tube, where they can be easily removed by grinding.

Solidification is influenced by the mold material and the rate of heat extraction from it, the thickness and thermal conductivity of the mold wash (liner) used, the pouring temperature and pouring rate of the alloy, the speed of rotation, and the presence of vibrations in the system resulting from less-than-perfect balance of the system. The structure of the resultant casting consists of a very fine columnar skin, a well oriented columnar structure adjacent to the skin, and an equiaxed structure at the inside diameter. The extent of each of these areas is determined by the type of metal poured and the pouring parameters.

Horizontal centrifugal castings are made in diameters up to 1.6 m (63 in.), with wall thicknesses of up to 200 mm (8 in.). The process is also used to make duplex and bi-metallic castings, in which the outer metal is cast first and acts as a mold for the second metal, which is cast inside it.

Vertical centrifugal casting can be subdivided into two types: semicentrifugal and centrifuging. In semicentrifugal casting, the casting configuration is determined entirely by the shape of the mold, and cores may be necessary if the casting has hollow sections. The process has the advantage over static casting: the centrifugal force completely fills the casting and feeds it. Thin-wall castings are especially helped by the process. In centrifuging, the casting cavities are arranged about the center axis of rotation like spikes of a wheel; the method is widely used in producing jewelry. Sand, metal, and investment casting molds may be used in this process. Figure 25 shows a vertical axis centrifugal casting machine.

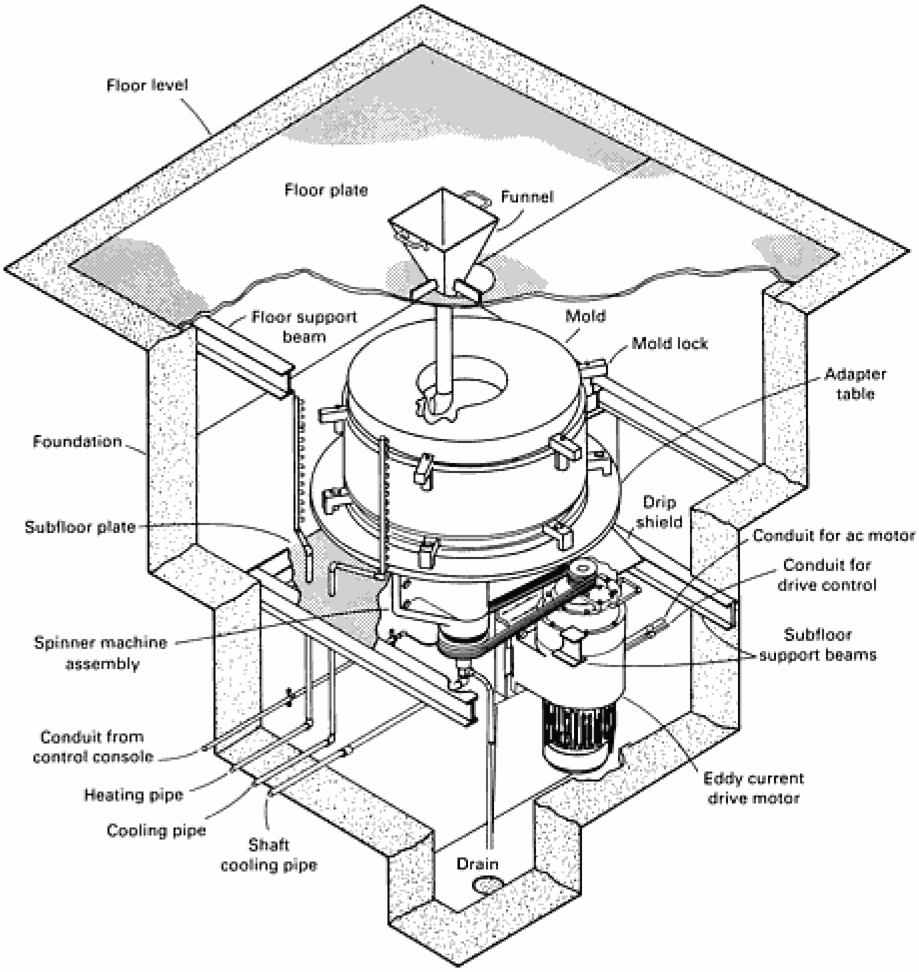

Floor level
Floor plate
Funnel
Floor support beam
Mold
Mold lock
Adapter table
Foundation
Drip shield
Subfloor plate
Conduit for ac motor
Conduit for drive control
Spinner machine assembly
Subfloor support beams
Conduit from control console
Heating pipe
Cooling pipe
Shaft cooling pipe
Drain
Eddy current drive motor

Fig. 25 Typical installation of a vertical centrifugal casting machine. The equipment is controlled from a remote console (not shown).

Casting structure will depend, as in horizontal centrifugal casting, on the speed of rotation and the pouring parameters. In some cases, the molds will be poured at a slow rotational speed, which is increased during solidification. Vibration from lack of balance in the system may cause casting problems.

Melting Methods

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Introduction

THE MELTING PROCESS includes the steps of making up the metal charge and melting it. It often includes refining (adjusting the chemistry of the melt using reactions in the molten metal bath) and treating the metal (adding small amounts of materials that affect the nucleation and growth of the solid during solidification). Melting furnaces derive their energy from combustion of fossil fuels or from electric power. The choice of which type of melting to use depends on a number of factors: type of alloy being melted, the local cost of electric power, and local environmental regulations.

Induction Melting

The most common melting method in use in foundries is induction melting. In this technique, heat is generated in the metal charge by induced currents resulting from the electromagnetic field established in the furnace by a coil surrounding the furnace. This electromagnetic field not only causes the charge to heat, but also exerts a force on the molten metal that stirs it, assuring excellent mixing in the metal bath. The two types of induction furnaces are channel furnaces and coreless furnaces.

Channel Induction Furnaces

In channel induction furnaces (Fig. 1), a small channel of molten metal surrounds the inductor coil. Only the small amount of metal in the inductor channel receives enough energy to be heated, and it is pumped out of the channel by electromagnetic forces into the remainder of the bath, which it heats by mixing. Because only liquid metal can enter the channel around the inductor, channel furnaces must be charged with liquid metal to start a melting cycle, and, when the liquid bath is tapped, some liquid must remain in the furnace to start the next heat. When the furnace is not in use (nights and weekends) power must be left on the furnace to keep this liquid from freezing. Because only a small amount of liquid in the channel receives electrical energy, use of this method as a primary melting source is slow. For this reason, channel furnaces are primarily used as holding or refining furnaces.

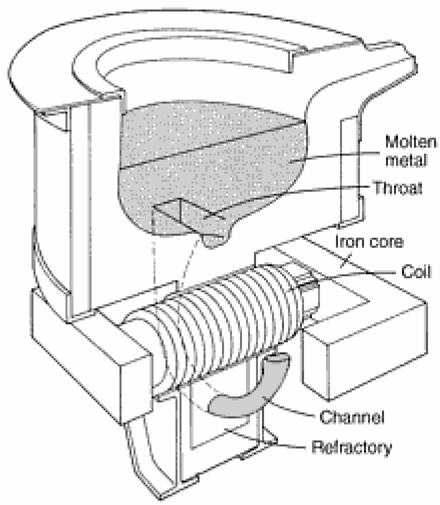


Fig. 1 A cross section of a channel-type induction furnace showing the water-cooled copper induction coil that is located inside of a 360° loop formed by the throat and channel portion of the molten metal vessel. It is the channel portion of the loop that serves as the secondary of the electrical circuit in which the copper coil is the primary.

Channel furnaces may be horizontal or vertical in design. They generally operate on 60 cycle current, although other melt frequencies are possible. Power requirements may be as low as 20 kW for 315 kg (700 lb) capacity to 200 kW for 1360 kg (3000 lb) capacities. Melt rate can vary from 45 to 450 kg/h (100 to 1000 lb/h). Because only the liquid in the area of the inductor is stirred, mixing in the channel furnace is less efficient than in the coreless induction furnace. However, channel furnaces have high electrical efficiency and are simpler than coreless furnaces.

One problem encountered in coreless furnaces is clogging of the channel during operation. Clogging is caused by the products of the reaction between the refractories that line the furnace and the alloy being melted. At melting temperatures, the refractories react with the molten alloy to some extent. In some cases, the refractories are deliberately selected to produce reactions that refine the metal. These reactions are the cause of refractory degradation and determine the life of the refractory in the furnace. While the clogging reactions are the same in channel and coreless furnaces, the reaction products are visible in coreless furnaces but are out of sight of the melter and concentrated in the channel in channel furnaces. Care must be taken to monitor the condition of the channel during tapping to avoid unexpected interruptions of melting caused by clogging.

Coreless Induction Furnaces

In the coreless induction furnace (Fig. 2), the metal is surrounded by a hollow copper tube wound in a spiral. The tube is hollow to allow cooling water to run through and carry away heat generated in the copper by the induced current. The coil is firmly supported so it does not change shape under the influence of the field, and a refractory lining protects it from physically contacting the molten bath. Coreless furnaces allow cold-charge melting, and refining may be carried out by adding refining elements and removing the reaction slag from the surface of the furnace. Emissions are substantially less using coreless induction melters than some fossil-fuel melters, such as cupolas. Induction furnaces also operate efficiently in a vacuum and are the primary power supply for vacuum melting.

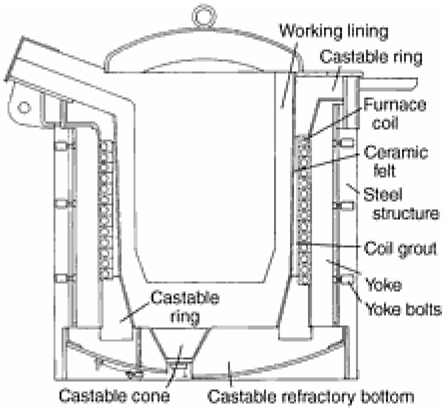

Working lining
Castable ring
Furnace coil
Ceramic felt
Steel structure
Coil grout
Yoke
Yoke bolts
Castable ring
Castable cone
Castable refractory bottom

Fig. 2 A cross section of a coreless-type induction furnace showing water-cooled copper induction coil and key structural components. The entire molten metal bath (which serves as the secondary) is surrounded by the coil (the primary) that encircles the working lining.

The entire bath is heated and stirred by the electromagnetic field, as shown in Fig. 3. This stirring allows excellent alloy and charge absorption and aids in producing a melt that is thermally and chemically homogeneous. The amount of stirring depends directly on the amount of induced power and inversely on the square root of the frequency of the furnace. Selection of the wrong frequency will result in either too little or too much stirring and substantial melt inefficiency. In general, too much stirring will stand the melt up in the furnace, away from the furnace walls ("haystacking"), and expose the melt to the air. Because the oxygen in the melt reacts with most metals, this exposure leads to excessive melt-oxidation losses. However, this effect has been used to advantage in the design of a vacuum furnace for melting highly reactive metals such as titanium; here the metal is deliberately kept from furnace walls by electromagnetic forces. The relationship between melt frequency and furnace size is shown in Fig. 4.

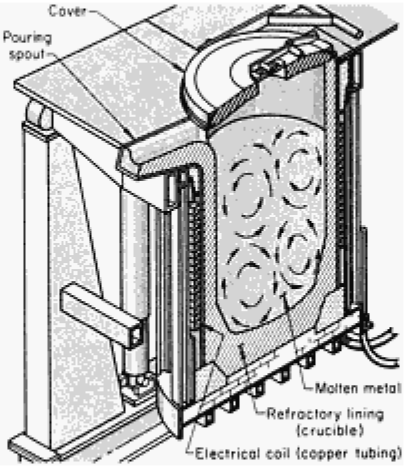

Cover
Pouring spout
Molten metal
Refractory lining (crucible)
Electrical coil (copper tubing)

Fig. 3 Sectional view of a coreless induction furnace. (Arrows in crucible show direction of stirring action.)

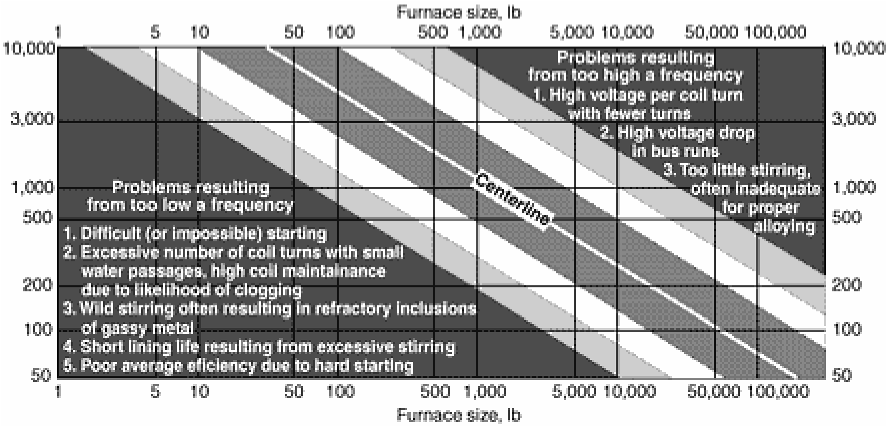


Fig. 4 Furnace size versus frequency for coreless induction melting of ferrous alloys. Frequency versus furnace size selections made along the centerline (and surrounding dark shaded area of chart) represent extremely successful melting applications. In the adjacent white zone areas, caution is required. The light gray zones represent areas in which the furnaces will work but probably never should be used. The outer dark zones indicate areas that should be out of bounds. In applying this chart to aluminum, multiply the weight of the metal by three to arrive at the recommended furnace capacity.

Power Supplies

Many induction furnaces use line-frequency (60 cycle) power. However, a recent development is the use of high-power, medium-frequency furnaces for use in ferrous melting. In using line current, the typical power supply (Fig. 5) consists of the following:

- Primary switchgear
- Furnace transformer: needed to reduce the high voltage of the local power grid to the voltage required for melting
- Phase balancing system: needed because the induction furnace is a single-phase device, but the power is supplied from a three-phase system
- Power factor correction capacitor bank, needed to compensate for the amount of metal in the furnace and refractory wear (which changes the volume of the furnace)
- Instrumentation and controls

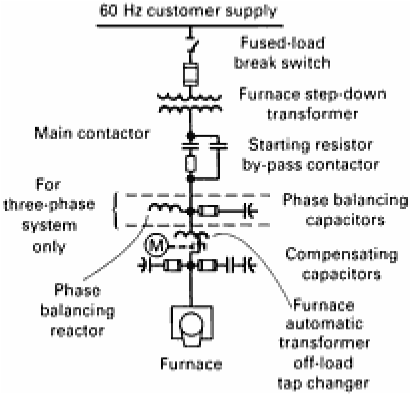

60 Hz customer supply
Fused-load break switch
Furnace step-down transformer
Main contactor
Starting resistor by-pass contactor
For three-phase system only
Phase balancing capacitors
M
Compensating capacitors
Phase balancing reactor
Furnace automatic transformer off-load tap changer
Furnace

Fig. 5 Modifying 60 Hz line frequency supplied by utility company to serve as power supply for induction furnaces

The typical conversion is an ac-dc-ac sequence. Although frequency conversion entails electrical losses, the solid state power supplies used in these furnaces have efficiencies approaching 97%. The power supplies are computer controlled to obtain maximum efficiency during melting. Two types of inverters are used, series and parallel. The furnace and compensating capacitor bank form part of a resonance circuit. In a series inverter, the capacitors are connected in series with the induction coil, and power to the furnace is controlled by detuning the inverter. In a parallel inverter, the capacitor bank is connected in parallel with the induction coil, and power is controlled by detuning the inverter in the full-power range. Thyristors in the rectifier lower the dc voltage and provide half cycle protection. Parallel systems are most widely used.

Furnace Linings

Furnace linings may be acid (silica-base), neutral (alumina-base), or basic (magnesia-base), depending on the alloy being melted. Silica is usually used for ferrous heats because it does not react extensively with the acid slag produced by the high silicon-containing iron compositions. It is inexpensive, and its thermal expansion is flat above 815 °C (1500 °F). Alumina is generally used with aluminum alloys, and magnesia linings are used with steel compositions that require a basic refractory to maintain proper composition. Alumina and magnesia have less thermal shock resistance than silica. In most cases the refractory is applied as a ramming mix, in which the refractory is combined with a sintering aid, such as boric acid. When the lining is sintered, the high temperature reached at the melt surface of the lining forms a hard glazed surface.

Melting Operations

Induction furnaces may be operated either in a batch mode, in which the entire charge is emptied and a new charge is melted, or a tap-and-charge mode, in which only a portion (typically one-third) of the melt is emptied, and new charge materials are added to the remaining charge and melted in. The batch operation has a somewhat higher melting efficiency, but chemistry is easier to control in tap-and-charge operation, as only one-third of the furnace charge must be added.

In foundry melting, the charge usually consists primarily of scrap and foundry returns (gates, risers, and scrapped castings). Chemistry is adjusted by adding the elements needed to reach the proper composition. Scrap must be preheated before charging to burn off machining oil, which can contaminate the charge and drive off all moisture, adding unwanted hydrogen to the bath, and, if enough water is present, causing a steam explosion when charged into the furnace.

Note that the same reactions that cause clogging in channel furnaces also cause refractory build-up in coreless furnaces. In coreless furnaces, the buildup is found at the bath-atmosphere interface near the top of the furnace. As the lining wears, the diameter of the furnace changes, changing the coupling characteristics between the power supply and the melt. The computer-controlled power supply automatically compensates for these changes. It is essential that the lining not be permitted to wear through to the coil, which will quickly melt and allow the cooling water to enter the molten bath with catastrophic results.

Cupola Melting

Cupolas are vertical shaft furnaces used for melting cast iron. Although similar in principle to blast furnaces, they are not "miniature blast furnaces." In operation, coke, flux, and metal are charged into the top of the furnace, and air, often preheated and/or enriched with oxygen, is blown in at the bottom through tuyeres. The coke burns in the air, melting the metal that trickles down to the bottom of the furnace or well, where it is tapped. Sectional views of cupolas are shown in Fig. 6.

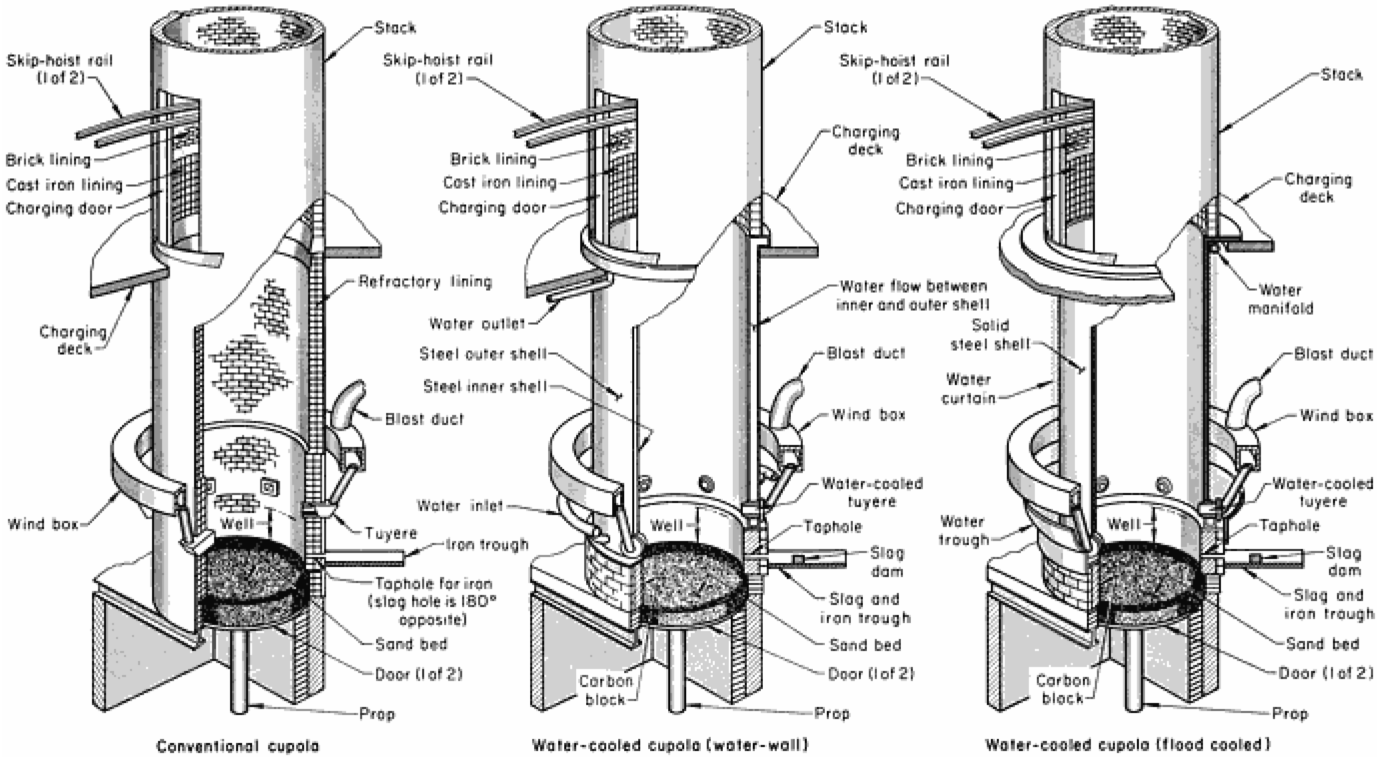

Stack
Skip-hoist rail (1 of 2)
Brick lining
Cast iron lining
Charging door
Charging deck
Refractory lining
Blast duct
Wind box
Well
Tuyere
Iron trough
Taphole for iron (slag hole is 180° opposite)
Sand bed
Door (1 of 2)
Prop
Conventional cupola
Stack
Skip-hoist rail (1 of 2)
Charging deck
Brick lining
Cast iron lining
Charging door
Water flow between inner and outer shell
Water outlet
Steel outer shell
Steel inner shell
Blast duct
Wind box
Water-cooled tuyere
Water inlet
Well
Taphole
Slag dam
Slag and iron trough
Sand bed
Carbon block
Door (1 of 2)
Prop
Water-cooled cupola (water-wall)
Skip-hoist rail (1 of 2)
Stack
Brick lining
Cast iron lining
Charging door
Charging deck
Water manifold
Solid steel shell
Water curtain
Blast duct
Wind box
Water-cooled tuyere
Water trough
Well
Taphole
Slag dam
Slag and iron trough
Sand bed
Carbon block
Door (1 of 2)
Prop
Water-cooled cupola (flood cooled)

Fig. 6 Sectional views of conventional (non-water-cooled) and water-cooled cupolas. The conventional type shown is refractory lined. Water-cooled types incorporate either an enclosed jacket or an open cascade flow.

Cupolas are highly energy-efficient melting furnaces for cast iron. However, they produce large quantities of particulate and exhaust gases. These emission products must be removed from the gases discharged to the atmosphere, and the equipment required to accomplish this is expensive to purchase and operate. As a result, cupolas, despite their inherent simplicity and energy efficiency, are used only by the largest foundries, which require a high tonnage of molten iron in daily operation. The advantages of using cupolas in high-tonnage foundries include the fact that molten metal delivery is continuous, uninterrupted by the need to charge or melt new material.

As requirements on cast iron tighten, the cupola is used more and more as a bulk melter to provide metal for subsequent refining and treatment operations, usually carried out in induction furnaces or special treatment ladles, and less as a method of providing iron ready to be poured into molds. However, as a bulk melter, it is unsurpassed when large quantities of consistent-quality iron are required.

Refinements in Cupola Equipment

The concentration of cupola melting in high-tonnage applications has resulted in the development of refinements that increase the efficiency of the furnace.

Water Cooling. The refractory lining of cupolas wears because of abrasion of the charge materials and chemical reactions with the charge. These are accelerated at high temperatures.

Cooling the cupola wall with water significantly extends the refractory life and reduces downtime for relining. In fact, the refractory lining may be completely eliminated from the melting zone of the cupola. With water cooling, cupolas may operate continuously for 24 h periods, going weeks before requiring relining and maintenance.

Preheated Air Blast. Although cupolas function without preheated air, the combustion reaction is enhanced by preheating the air to 540 to 650 °C (1000 to 1200 °F). The air is usually preheated using natural gas and recuperative hot blast systems that recover the heat of the exhaust gases from the cupola.

Oxygen Enrichment. Adding 1 to 4% oxygen to the blast increases the metal temperature and the melting rate.

Coke Injection. Fine particles of coke may be injected into the blast through the tuyeres to increase carbon content of the iron.

Basic Linings. Originally, cupola linings were silica, chosen for its low cost. Silica linings are acceptable for gray iron. However, ductile iron requires very low sulfur contents. These can only be obtained from a cupola by using a basic slag. As a result, basic linings, using dolomite and magnesia, have been developed. Because of the higher cost of basic linings, basic cupolas are water cooled.

Computer Control. Using sensors and computer programs that calculate the reactions taking place in the cupola, air blast, and temperature, as well as the amounts of coke, limestone, and metal to charge, can be controlled automatically.

Cupola Operation

Cupolas may be operated either continuously or intermittently. In continuous operation, the iron and slag formed in the melting operation flow from a tap hole in the wall of the furnace well. Because the slag that is formed is lighter than the iron, it floats and may be separated from the iron using skimming knives and dams. The metal from continuous melting is usually tapped into induction-heated holding and/or treatment furnaces. High-tonnage cupola operations are usually continuous.

Intermittent tapping cupolas have a tap hole for the iron and a separate tap hole, higher in the well, for the slag. The iron tap hole is closed with fireclay. As molten metal accumulates in the well, its level rises until the slag reaches the level of the slag hole where it flows from the cupola. The iron tap hole is then opened, and the iron in the well drains out. The tap hole is closed and the process is repeated. The iron tap hole may be opened more frequently if desired.

Charge Materials

The metallic part of the charge is made up of foundry returns, pig iron and cast iron, and steel scrap. Gates, risers, and internally generated foundry scrap generally constitute 30 to 50% of the charge. Steel scrap is the next most prominent component of the charge. It offers the advantage of having low phosphorous content, essential for ductile iron. Cast iron scrap is also used, and pig iron is added to adjust the quality of the iron. Pig iron has a low level of tramp elements, and thus it can be used to bring melts contaminated by tramp elements from the scrap charge into specification. Careful analysis of scrap charges and proper mixing of scrap in the charge are necessary to provide consistent melt-composition control.

Ferroalloys. Because cast iron contains silicon and manganese, these elements must be added when steel scrap and pig iron are used in the charge. Ferrosilicon (50 or 75% Si) and ferromanganese (80% Mn) are usually added. Other forms include silvery pig (16 to 20% Si), silicon carbide (which also deoxidizes the iron), spiegel (10% Mn), and briquettes of silicon and manganese.

Coke is often considered to be the most important of the charge materials. Foundry grade coke is generally of higher quality than blast furnace coke. It must be strong enough to support the charge and to be sized properly, meaning that the size and size distribution of the coke must be controlled. Low ash content is desirable, and low sulfur content is particularly important, especially in ductile iron foundries. Coke comprises between 8 and 16% of the weight of the metallic charge.

Fluxes are added to fluidize the oxide slags that form on the surface of the metal from reactions taking place during melting. Limestone (96% $CaCO_3$) or dolomite (96% $MgCO_3$) are usually added at the 2 to 5% level in acid cupolas, and more basic fluxes are added to basic cupolas to fluidize the slag. Soda ash is a strong slag fluidizer. Fluorspar (CaF_2) is a particularly powerful fluidizing agent, useful especially in acid cupolas to remove highly viscous slags. However, its use is limited by environmental considerations.

Melt Rate

The cupola is expected to maintain a melt rate that feeds the molding capacity of the foundry. However, as the size of the castings produced during the day may change, the volume of iron required may also change. The melt rate can be varied ±20% by increasing or decreasing the blast. Tap temperature must be high enough to allow metal transfer to the molds, filling them without misrun, or to the next refining or treatment operation without freezing. Tap temperature is primarily influenced by the coke content in relation to the metal charge. The carbon and silicon content must be closely controlled.

Sulfur content in gray iron must be kept below 0.12%, but in ductile iron it must be below 0.015%. Phosphorous levels are generally kept as low as possible to improve machinability and impact resistance in ductile iron.

Control Tests and Analyses

Traditionally, cupola melt control was carried out by using the "chill test." In this test, a wedge-shaped bar of iron is poured and allowed to solidify. After it is solid, it is broken across the cross section and visually examined for the depth of white iron ("chill"), which is an indication of the carbon and silicon content. This test is still used, but it is augmented by eutectic temperature-arrest measurements, which are rapid and more accurate, and spectrometer analyses.

Computer Use in Cupola Operation

The chemical and thermal reactions that take place in a cupola have been modeled mathematically, to gain insight into improved control methods for cupolas. Computers are capable of controlling the entire operation of the cupola, in a feed-back or feed-forward mode. The use of computer controls on cupolas allows automatic continuous adjustment of melt variables to minimize cost and effluent production. In one version of computer control, a mathematical model of the operation of the cupola checks the actual operation and adjusts melting parameters to optimize cupola operation.

Arc Furnaces

Electric arc furnaces are used almost exclusively for melting steel, although some iron is melted in them, and they may be used as holding or refining furnaces. Arc furnaces may be direct current or alternating current. In either case, power to the furnace is provided by an arc established between a graphite electrode and, in the case of direct current furnaces, the charge. In the alternating current arc furnace, the arc is established between the electrodes through the charge.

Types of Furnaces

A cross section of an alternating current electric arc furnace is shown in Fig. 7. Two different types of furnace are shown: acid practice and basic practice. The difference is in the furnace linings used; in acid practice the lining is rammed silica or ganister (a silicaceous refractory), and in basic practice the lining is rammed magnesite or dolomite. The acid practice offers flexibility in melting a variety of compositions, lower refractory and power costs than a two-slag basic practice, and greater tonnage per unit time. The basic practice is used to remove sulfur and phosphorous (in a two-slag practice), and it is used for stainless steel melting. In either case, the power is supplied from the local utility through a substation designed expressly for the furnace.

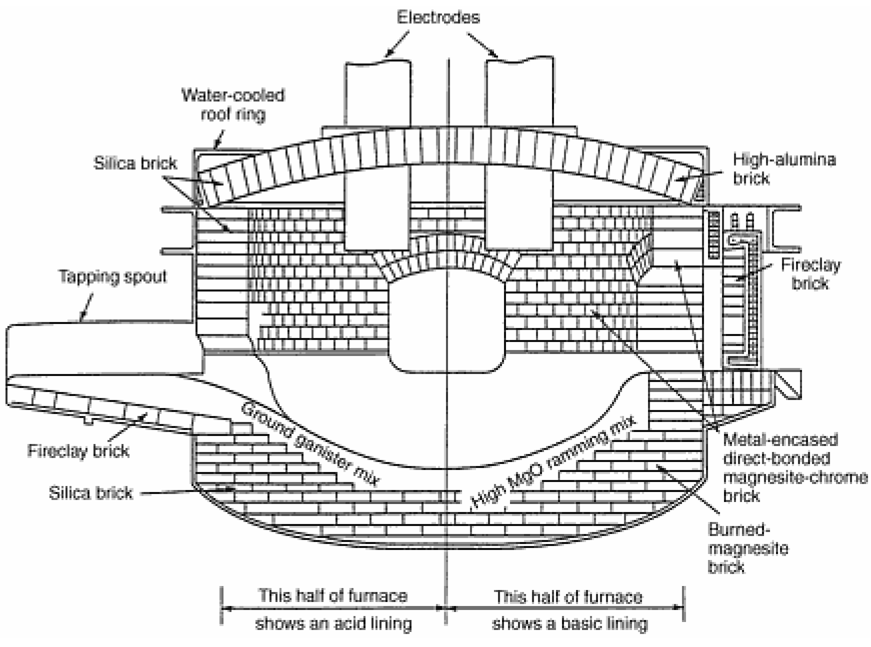

Electrodes
Water-cooled roof ring
Silica brick
High-alumina brick
Fireclay brick
Tapping spout
Ground ganister mix
High MgO ramming mix
Fireclay brick
Silica brick
Metal-encased direct-bonded magnesite-chrome brick
Burned-magnesite brick
This half of furnace shows an acid lining
This half of furnace shows a basic lining

Fig. 7 Cross-sectional view of an electric arc furnace indicating typical refractories employed in acid and basic

linings.

In acid practice, the furnace is charged with materials low in sulfur and phosphorous. The material will usually consist of 30 to 50% returns (scrap, gates, and risers) and 50 to 70% purchased scrap. Heavy scrap and casting returns are usually placed on the bottom of the furnace with lighter scrap on top. Nonoxidizing alloying elements, such as nickel and molybdenum, may be added with the charge. The arc is struck, and the charge is melted down rapidly. A carbon boil is then carried out to lower the carbon content. In the carbon boil, oxygen reacts with the carbon in the charge to form carbon monoxide gas that is removed from the furnace. The boil is produced either by using an oxygen lance or by adding mill scale (Fe_3O_4) as a source of oxygen. In many cases, the rust on the charge is sufficient to produce the carbon boil. A vigorous boil eliminates all of the carbon, most of the hydrogen, and some nitrogen from the charge. A slag forms on the surface of the melt from the oxides produced from the silica lining and dirt on the charge.

After decarburization the boil slows to a gentle roll, and recarburization and alloy additions may be made if required. The recarburizers may be low-silicon, low-phosphorous pig, sorel pig iron, high-carbon pig iron, or even broken electrodes. When the desired carbon level is reached, the oxidation reactions are stopped by adding silicon and/or manganese in the form of ferroalloys. Once the final alloying elements have been added, the heat is tapped.

In basic practice, the charge is similar (except that lower purity charge materials may be used), and a carbon raiser (coke, high-carbon pig, etc.) and limestone are added with the charge. The lime removes sulfur from the charge, and the slag it forms protects the bath. The bath is oxidized as before to adjust the carbon content of the melt. When the oxidizing period is over, the bath may be tapped if a single slag practice is being used. However, if it is desirable to remove phosphorous from the heat, a different procedure is followed. Iron ore or mill scale is added to the slag when melting is complete to raise the oxygen content of the slag so that phosphorous can be oxidized. Silicon content in the bath is kept low, and the temperature is kept below 1540 °C (2800 °F), as the dephosphorizing reaction reverses above this temperature. After the phosphorous level has been reduced, the slag (that now contains the phosphorous) is removed from the furnace, and a second slag is formed from limestone. As soon as the second slag is melted, the current is reduced, and a deoxidizer such as coke, coal, or aluminum is added. These elements reduce the oxides of iron and manganese in the slag and help form a calcium carbide slag that removes sulfur. After the proper levels of carbon are reached, the temperature is raised for tapping, and the furnace is emptied.

Following the practice in the basic steel industry, refining may also be carried out in ladles. Deoxidizers in the form of aluminum or titanium are added to remove oxygen so the carbon content of the heat does not change during pouring. A number of other refining practices may be used for high-alloy steels to assist in the recovery of alloy elements needed for the final composition. Argon stirring may be used to remove inclusions, and calcium wire injection is often used to improve steel cleanliness.

The Direct Current Arc Furnace

In the direct arc furnace, shown in Fig. 8, only a single electrode is used. This method of melting is slowly growing in use. It has become feasible through the development of high-power solid-state converters. Its advantage is that it has a simpler circuit than the three-electrode alternating current method, and electrode consumption is greatly reduced. The single electrode is connected to the cathode of the rectifier, and the anode is connected to the furnace bottom. The charge passes from the electrode through the charge to the furnace bottom. Melting in a direct current furnace takes longer unless a heel of molten metal is left in the furnace.

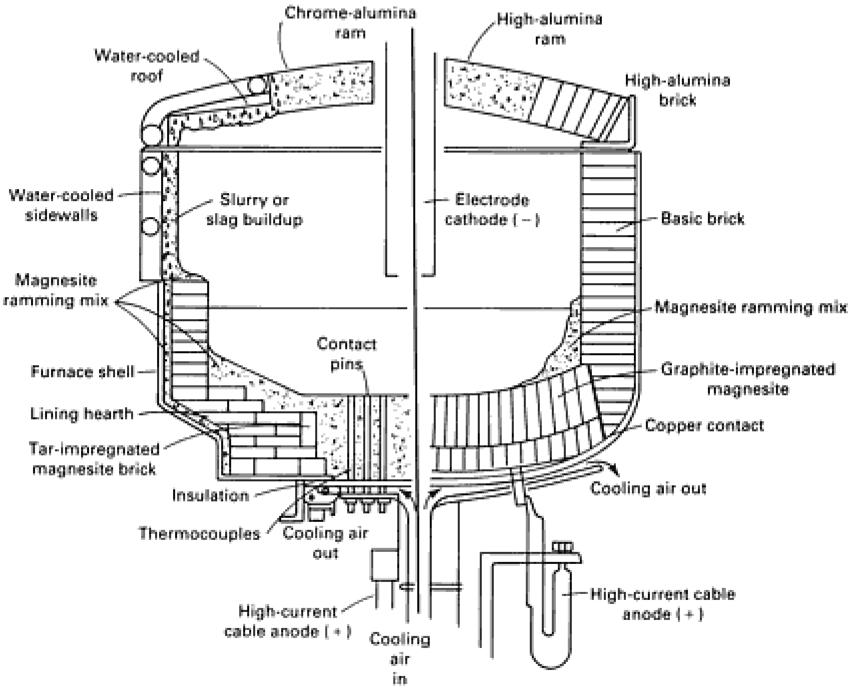

Chrome-alumina ram
High-alumina ram
Water-cooled roof
High-alumina brick
Water-cooled sidewalls
Slurry or slag buildup
Electrode cathode (−)
Basic brick
Magnesite ramming mix
Magnesite ramming mix
Contact pins
Furnace shell
Graphite-impregnated magnesite
Lining hearth
Copper contact
Tar-impregnated magnesite brick
Insulation
Cooling air out
Thermocouples
Cooling air out
High-current cable anode (+)
High-current cable anode (+)
Cooling air in

Fig. 8 Sectional view showing the basic components of a direct current arc furnace

As in other melting methods, the scrap should be preheated, and dust and fume hoods are required in the installation to avoid air pollution. Tapping is carried out by tilting the furnace and allowing the molten metal to run into the ladle.

Crucible Melting

Crucible furnaces are used to melt aluminum, zinc, magnesium, and copper alloys. In these furnaces, shown in Fig. 9 and 10, natural gas or a petroleum fuel is burned, and the flame surrounds the crucible. Crucible furnaces can also be used in induction melting.

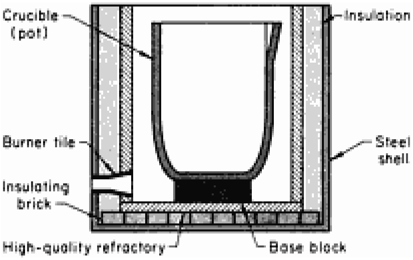

Crucible (pot)
Insulation
Burner tile
Steel shell
Insulating brick
High-quality refractory
Base block

Fig. 9 Lift-out crucible (pot) furnace

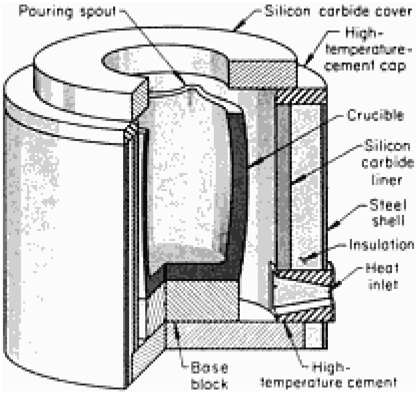

Pouring spout
Silicon carbide cover
High-temperature-cement cap
Crucible
Silicon carbide liner
Steel shell
Insulation
Heat inlet
Base block
High-temperature cement

Fig. 10 Typical lift-out crucible furnace especially well adapted to foundry melting of small quantities of copper alloys (usually less than 135 kg, or 300 lb)

Furnace Types

In stationary furnace installations, the crucible is set inside a refractory-lined shell. When the metal is molten, it is dipped out using a hand ladle, or the crucible is removed using tongs, placed in a yoke, and transported to the molds. In a push-out furnace, shown in Fig. 11, hydraulic cylinders raise the crucible out of the furnace where it may be transferred to the pouring line. The crucible material is chosen according to the alloy being melted. Clay graphite crucibles are used for aluminum, and steel or ductile iron crucibles may be used for magnesium and zinc. Other refractories may be selected, depending on the alloy. Crucible furnaces may also be used as tilting installations, particularly when induction heating is used.

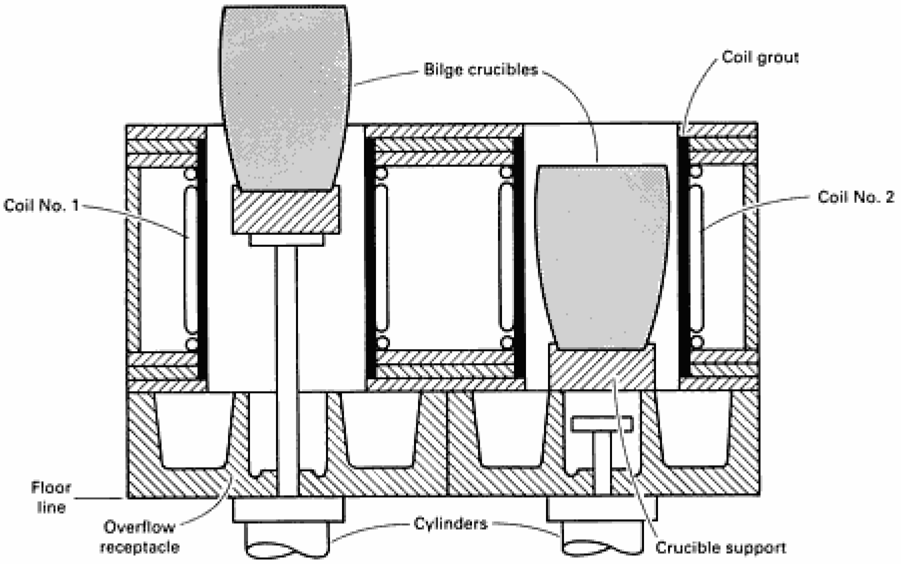

Bilge crucibles
Coil grout
Coil No. 1
Coil No. 2
Floor line
Overflow receptacle
Cylinders
Crucible support

Fig. 11 Cross section of a double push-out stationary crucible furnace

Burner Design. When natural gas is used for melting, care must be taken to degas the molten alloy. This is particularly true for aluminum heats, as molten aluminum has a very high solubility for hydrogen. In using natural gas or petroleum fueled furnaces, care must be exercised to keep the flame slightly oxidizing. Burner design and placement are important to avoid hot spots in the crucible that will wear more rapidly than desired. Melting is most efficient when a heel of molten metal is left in the furnace between charges. Care must also be taken when charging refractory crucibles to lay the charge in gently so that the crucible is not broken. The charge must also be loosely packed because the thermal expansion of a tightly packed charge as it heats to the melting temperature may break the crucible.

Resistance Heating. Crucible furnaces may also use electric resistance heating. This method is used in melting magnesium and aluminum alloys. Electric resistance furnaces have high-energy conversion efficiency and can be sealed to prevent updrafts in the furnace from carrying heat out the top of the installation.

Reverberatory Furnaces

Furnace Types

Reverberatory furnaces are used primarily for melting aluminum. They are of two types, wet hearth, shown in Fig. 12, and dry hearth, shown in Fig. 13. In the wet-hearth furnace, the products of combustion are in direct contact with the top of the metal bath, and heat transfer is achieved by a combination of convection and radiation. In the dry-hearth furnace, the charge of solid metal is positioned on a sloping hearth above the level of the molten metal so the entire charge is completely enveloped by the hot gases. Heat is rapidly absorbed by the solid charge, which melts and drains from the sloping hearth into the wet holding basin. Although reverberatory furnaces are normally fuel-fired, dry hearth furnaces may use electric energy to heat the refractories.

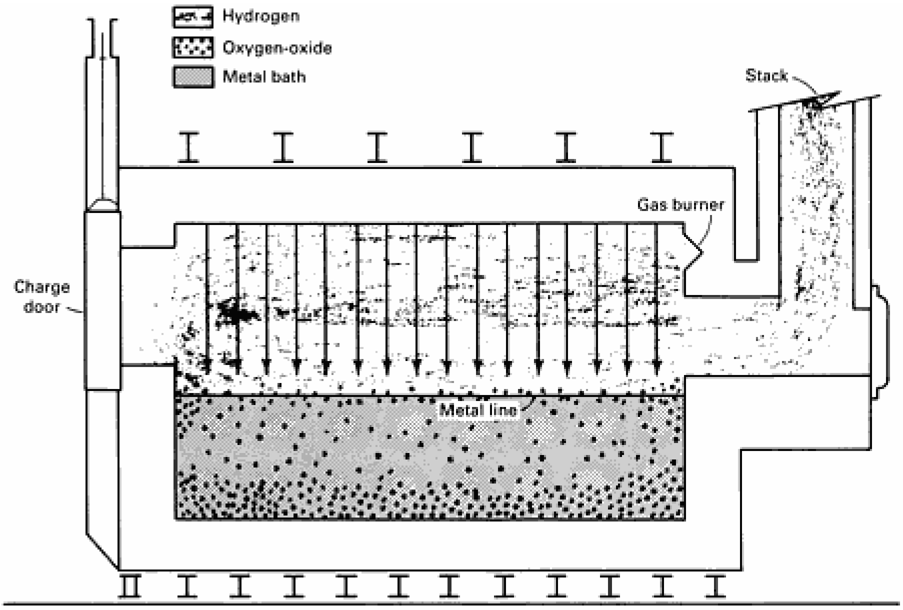


Fig. 12 Schematic of a wet-hearth reverberatory furnace heated by conventional fossil fuel showing the position of the hydrogen and oxygen gases relative to the molten metal bath. Arrows indicate heat radiated from top of furnace chamber.

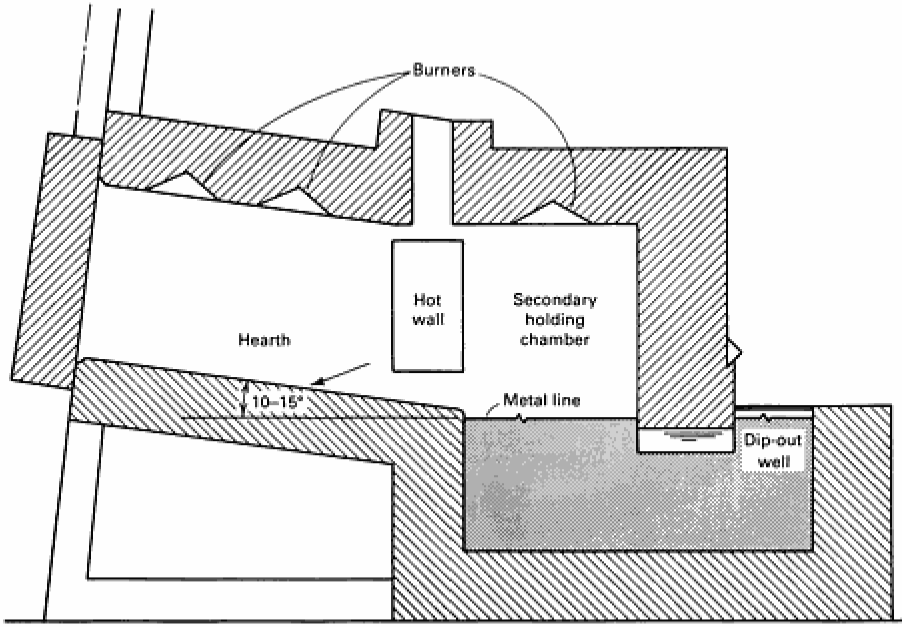


Fig. 13 Schematic of a radiant-fired dry-hearth reverberatory furnace illustrating the position of the sloping hearth relative to the molten bath

Refractories

Refractory selection depends on the metal being melted. In aluminum melting, care must be taken to remove the dross (aluminum oxide) that builds up on the surface of the melt and deposits at the melt line on the refractories. In aluminum alloys containing iron, often used in die casting, iron aluminum compounds may form a sludge, which sinks to the bottom of the furnace, and must be removed periodically. Refractory life is extended when the furnace operates continuously, including nights and weekends. The furnace is usually heated prior to charging, in order to close any cracks that may have formed on cooling from a previous campaign.

Charging Practice

During charging, light scrap is usually charged first, to act as a cushion for the heavier scrap and to protect the refractory. After the bath is molten, alloy additions are made. Light metal additions, such as magnesium and silicon, will float and oxidize on the surface instead of alloying; for this reason they should be submerged and held with a plunger until they have dissolved. Heavy elements, such as copper, will sink to the bottom of the bath and resist dissolution; they should be suspended in a basket. Zinc and tin often cause special problems, as they have low vaporization temperatures. When charged in large slabs, they sink to the bottom of the bath, and not only melt, but may vaporize. If the vapor enters the porous refractory, it may condense in the lower temperature areas of the furnace (near the furnace walls) and solidify. When the furnace is next heated, the solid metal expands and cracks the refractory. As in crucible furnaces, burner design and maintenance are important.

Reaction Melting

The heat of solution may also be used to melt alloys. This method has been particularly effective in melting nickel and titanium aluminides. In this process, a crucible is charged first with the higher melting material, nickel or titanium, and the lower melting material, aluminum, is placed on top of it. When the furnace is heated, the lower melting point metal melts, runs down over the nickel or titanium, and begins to dissolve it. The dissolution reaction is exothermic, which raises the temperature of the bath to the melting temperature of the intermetallic alloy, without the use of more energy. Because the exothermic reaction is so energetic, care must be taken to carefully arrange the charge in the furnace in layers; otherwise, the heat may be liberated so quickly that the crucible cracks.

Vacuum Melting

Vacuum melting is used for nickel-base superalloys, titanium alloys, and refractory alloys, to protect them from oxygen, which, in the case of the nickel-base alloys, forms deleterious inclusions, and in the case of titanium, could cause an exothermic reaction that would consume the heat and the furnace.

In vacuum induction melting (VIM), the induction furnace is enclosed in a steel chamber, as shown in Fig. 14. The chamber is connected to vacuum pumps that reduce the pressure in the chamber to 10^{-3} torr. The furnace may be charged with the door open to the atmosphere, or, in continuous operation, the charge is placed in the crucible through a charge lock. However, before melting, the door is closed, and the furnace and charge are pumped down to the vacuum level desired. Then power is applied and the charge is melted. Alloy additions are made through charge locks. The pressure in the charge lock is reduced to the pressure in the melting chamber before the lock is opened, and the alloying addition is made to the melt.

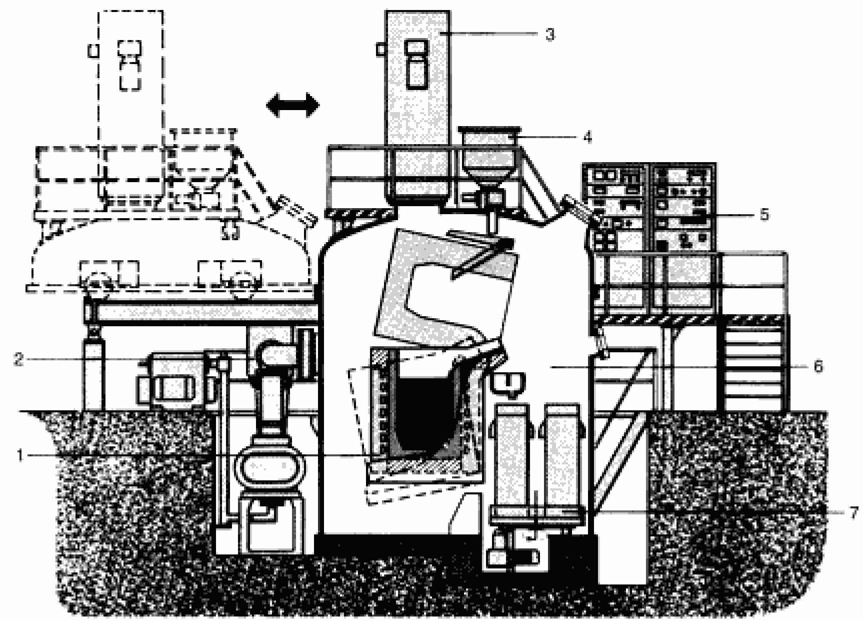


Fig. 14 Schematic of a typical VIM furnace. 1, furnace insert; 2, vacuum pumping system; 3, bulk charger; 4, fine charger; 5, control cabinets; 6, melting and mold chamber; 7, mold turntable

When the charge reaches the correct temperature, it is poured. In casting, the mold is moved, again through a charge lock, into the furnace and positioned beneath the lip of the furnace. The furnace is then tilted to fill the mold with molten metal. The mold is removed through a lock, and the cycle is repeated with a new charge and mold. Usually, the charge is a prealloyed ingot, weighed to contain exactly enough metal to fill the mold.

The vacuum induction furnace is a necessarily complex piece of machinery, consisting of the furnace and its power supply (which must be designed for vacuum operation to avoid arcing in the reduced pressure of the chamber), the pumps that evacuate the furnace (a series of pumps is required, as each pump design is most efficient over a fairly narrow range of reduced pressures), and the charge and mold locks that must include valves between them and the furnace chamber. Mold locks are frequently located beneath the melting chamber, so mold elevators must be employed to raise them to the furnace for pouring. The operation of the furnace is controlled automatically, depending on the output from temperature and vacuum gauges in the system.

Vacuum Arc Skull Melting. Very reactive alloys, such as titanium alloys, cannot be melted in refractory crucibles, because they violently react with or dissolve the refractory when they are molten. Instead, these materials are melted in water or NaK-cooled copper skull arc furnaces, such as that shown in Fig. 15. In this case, the alloy ingot is one electrode, and the copper crucible is the other electrode. The arc is struck from the ingot to the copper crucible, and the heat of the arc melts the ingot, which drips into the crucible. Because the crucible is cooled, the first metal that drips into it solidifies in it, forming a solid "skull" that contains the rest of the melt, thus avoiding contamination. The molds enter the furnace through a mold lock for pouring. When sufficient metal has been melted to fill a mold, the mold is placed in front of the crucible, the ingot rapidly retracted, and the crucible tilted. The pouring operation must be done quickly, or the metal will freeze in the crucible.

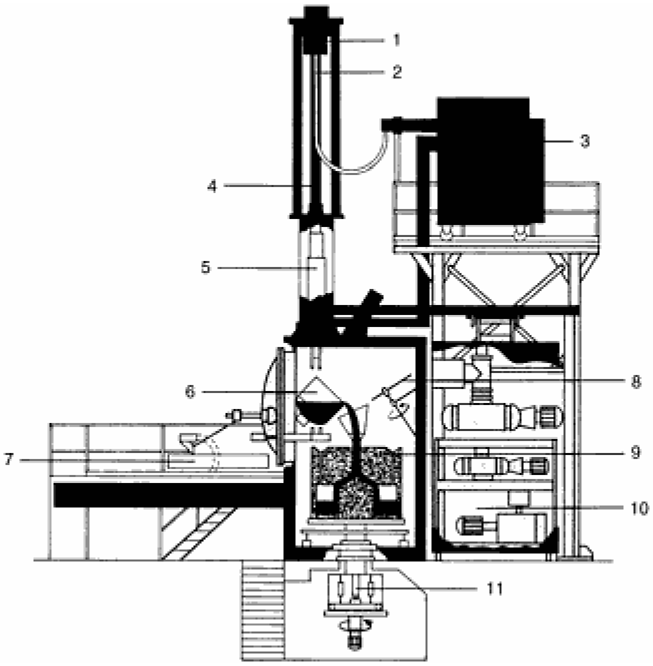


Fig. 15 Schematic of a modern semicontinuously operating vacuum arc skull melter for charge weights of up to 1000 kg (2200 lb). 1, fast retraction system; 2, power cables; 3, power supplies; 4, electrode feeder ram; 5, consumable electrode; 6, skull crucible; 7, crucible carriage; 8, tundish shield; 9, mold arrangement; 10, vacuum pumping system; 11, centrifugal casting system

Other Vacuum Processes. The disadvantage of vacuum arc remelting, or VAR, is the inability to control superheat accurately, as can be done in induction furnaces. This difficulty has led to the development of a vacuum induction furnace for reactive alloys in which the induction field is arranged so electromagnetic forces push the molten metal away from the walls of the furnace, standing it up in the center of the furnace. The molten alloy contacts the furnace wall only briefly during pouring, and there is little or no reaction with the wall.

Other power sources may be used in vacuum melting, such as plasmas or electron beams. However, these melting methods are not in widespread use in the foundry industry.

Molten Metal Treatment

There are a variety of molten metal treatments used to improve the quality of the metal charge. These are carried out in the ladles, rather than in the melting furnace.

Steels. In argon-oxygen-decarburization (AOD), used for stainless and alloy steel refining, oxygen, argon, and nitrogen are injected into the steel bath through submerged, side-mounted tuyeres (See Fig. 16 in the article "Steelmaking Practices and Their Influence on Properties" in this Handbook). This causes a shift in the decarburization thermodynamics, which permits the steel to be decarburized without oxidizing alloying elements such as chromium. During treatment, the ratio of oxygen to inert gas decreases as the carbon level decreases. Once the aim carbon level is obtained, a reduction mix (silicon, aluminum, and lime) is added. If extra-low sulfur levels are needed, a second desulfurization treatment can be carried out.

Steel heats may also be degassed using inert gas and vacuum. The melt is placed in the vacuum degassing vessel and the pressure above the melt is reduced, allowing hydrogen and nitrogen to be removed from the bath. To reach maximum effectiveness, the bath is stirred, either by electromagnetic forces, or by the injection of argon at the bottom of the ladle, (Fig. 16).

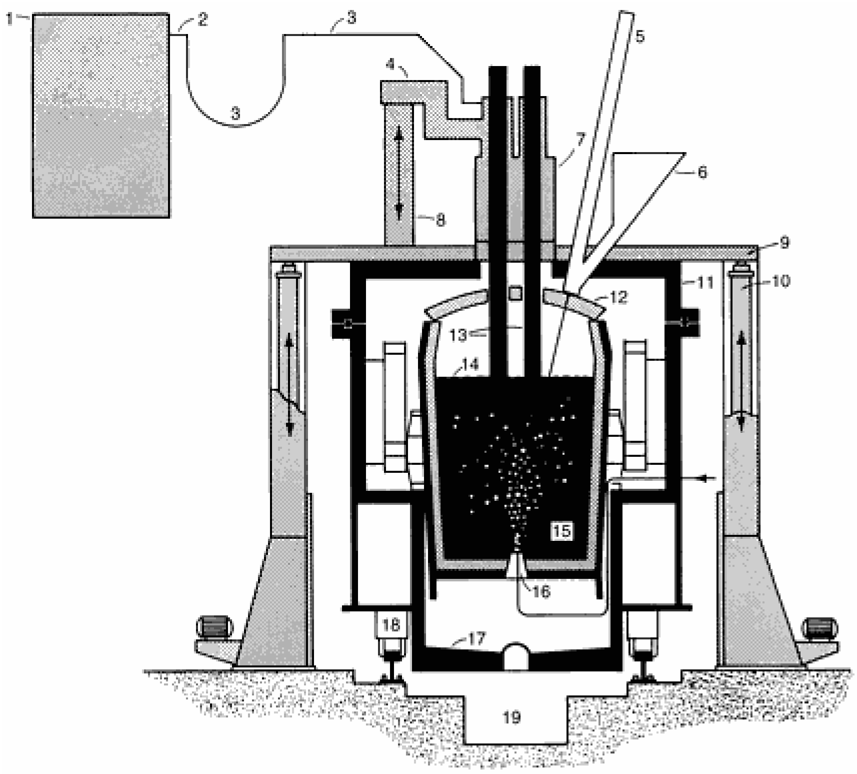


Fig. 16 Schematic of a vacuum arc degassing plant layout. 1, transformer; 2, bus bars; 3, flexible cables; 4, electrode arms; 5, temperature-measuring and sampling device; 6, alloying lock; 7, electrode housing; 8, electrode masts; 9, operating platform; 10, lifting device for platform; 11, vacuum cover; 12, ladle heat shield; 13, electrodes; 14, slag; 15, melt; 16, argon plug; 17, vacuum vessel; 18, vessel drive; 19, emergency pit

Aluminum heats must also be degassed to remove dissolved hydrogen that, if not removed, forms porosity in aluminum castings. The most efficient degassing method is to introduce chlorine gas, which reacts with the hydrogen to form HCl. However, because of safety concerns with chlorine, this method is little used. Instead, rotary degassing is used (Fig. 17). In this process, an inert gas is injected into the column or shaft of the rotator and is released through fine openings at the base of the rotor. When rotating at speeds of 300 to 500 rpm, the disperser shears the incipient gas bubble released, producing a wide dispersion of very fine bubbles for degassing. The high surface area to volume ratio provides a greatly increased contact area and increases reaction kinetics, resulting in more efficient degassing.

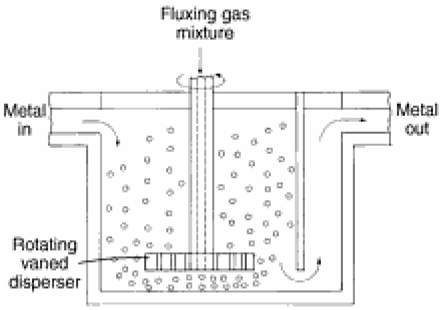


Fig. 17 Schematic of an in-line rotary degassing unit

Foundry Practice for Ferrous Alloys

Thomas S. Piwonka, The University of Alabama

General Considerations for Cast Irons

CAST IRON usually refers to an in situ composite of stable eutectic graphite in a steel matrix. The shape of the graphite is controlled by treating the liquid metal before solidification begins, in order to control the amount of undercooling the melt undergoes before solidification begins. In one form of cast iron referred to as white iron, the metastable form of the eutectic, iron carbide (Fe_3C), is formed. The difference between the stable and the metastable phase diagrams of the iron-carbon system is shown in Fig. 1. A general diagram showing a simplified process chart for cast iron is presented in Fig. 2. A significant foundry property of cast iron is that when the stable eutectic, graphite, forms on solidification, it expands rather than shrinks. This means that many iron castings can often be made with minimum use of risers.

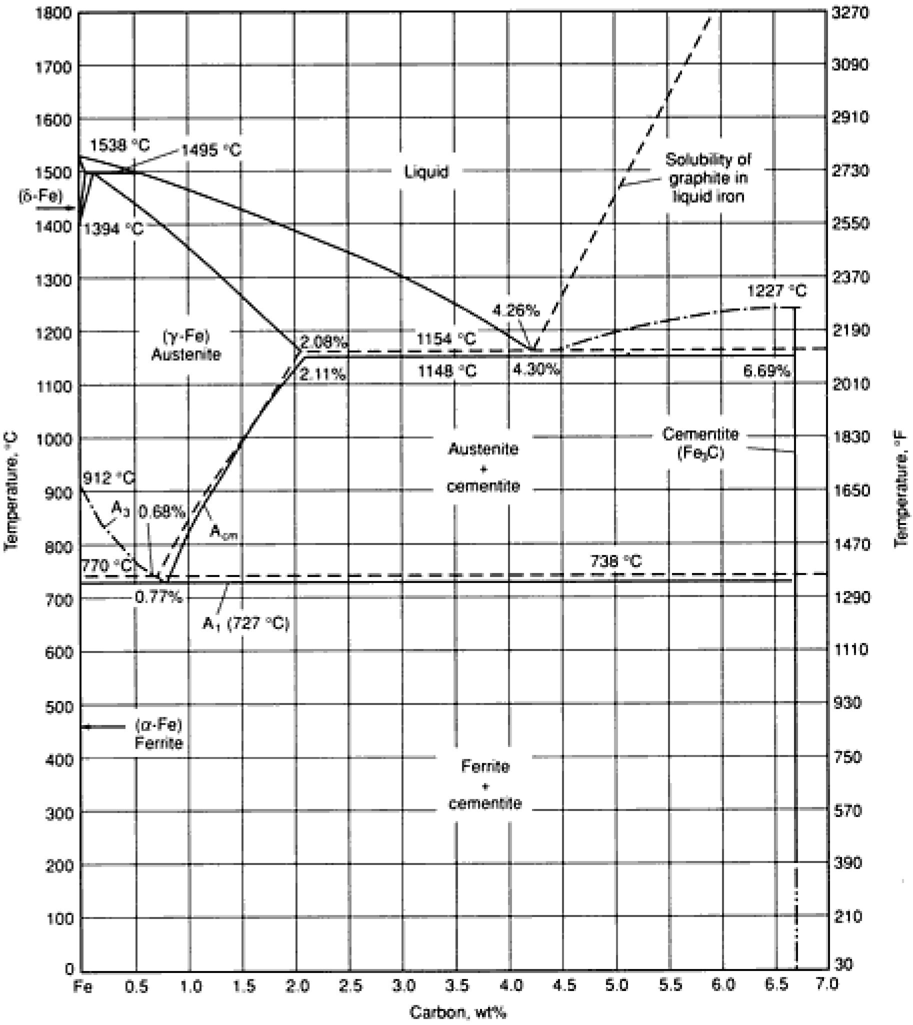


Fig. 1 Iron-carbon diagram, where solid curves represent the metastable system Fe-Fe_3C and dashed curves represent the stable system iron-graphite

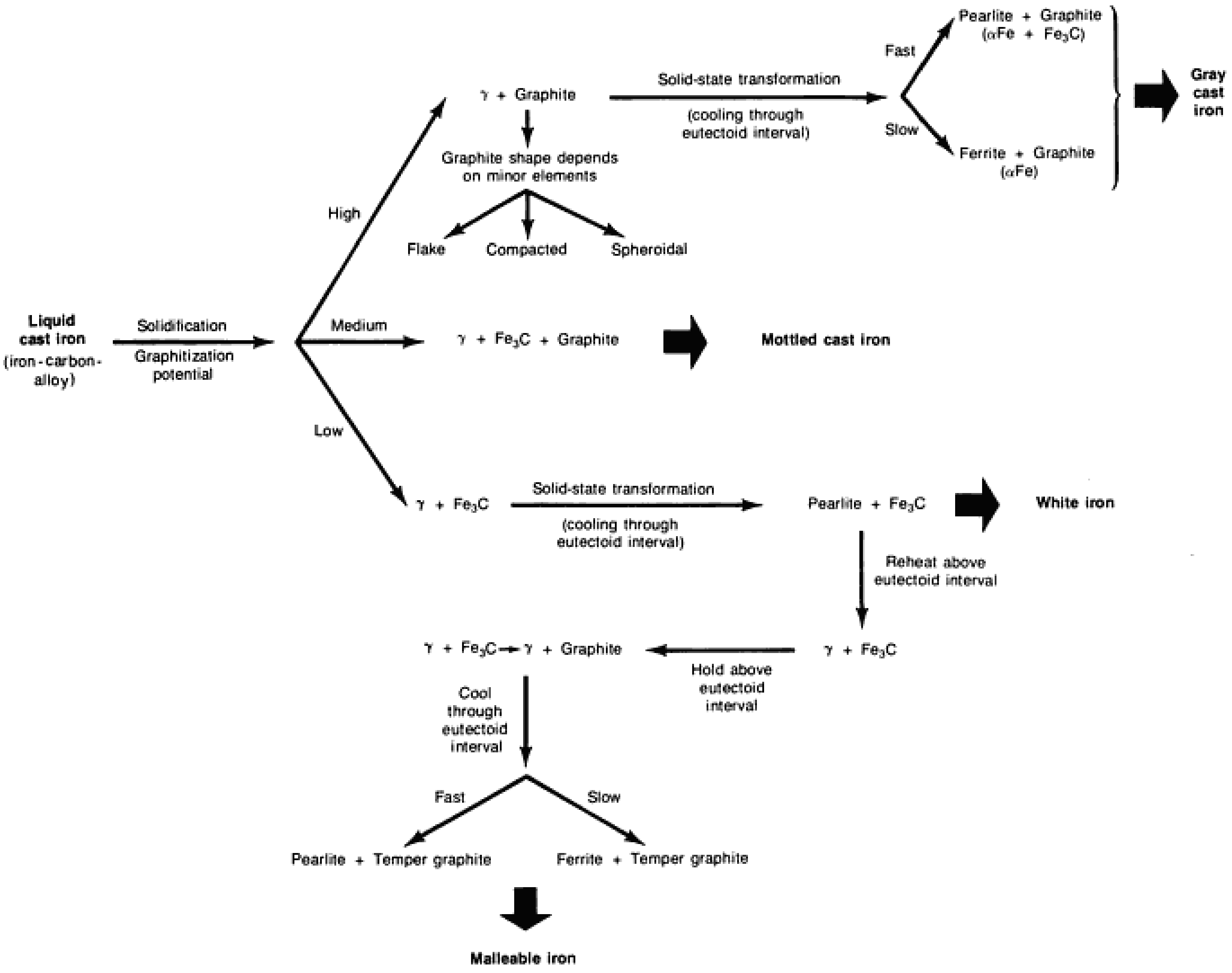

Liquid cast iron (iron-carbon-alloy)
Solidification
Graphitization potential
High
Medium
Low
γ + Graphite
Graphite shape depends on minor elements
Flake
Compacted
Spheroidal
Solid-state transformation
(cooling through eutectoid interval)
Fast
Slow
Pearlite + Graphite (αFe + Fe3C)
Ferrite + Graphite (αFe)
Gray cast iron
γ + Fe3C + Graphite
Mottled cast iron
γ + Fe3C
Solid-state transformation
(cooling through eutectoid interval)
Pearlite + Fe3C
White iron
Reheat above eutectoid interval
γ + Fe3C
Hold above eutectoid interval
γ + Fe3C → γ + Graphite
Cool through eutectoid interval
Fast
Slow
Pearlite + Temper graphite
Ferrite + Temper graphite
Malleable iron

Fig. 2 Basic microstructures and processing for obtaining common commercial cast irons

It is important to realize that "cast iron" refers to a family of materials, not a single material. Within the major classifications of cast iron, which include gray iron, ductile iron, compacted graphite iron, malleable iron, and white iron (referring to the form of the eutectic which forms on solidification), variations are produced by alloying and heat treating. These processes control the structure of the matrix. For this reason, cast irons can be used for a wide variety of applications. In many cases, more than one type of cast iron will satisfy performance requirements, so it is important to have a thorough knowledge of the possibilities to find the most economical iron for a specific use.

Cast iron is not poured into metal molds unless white iron is to be produced. Instead, molds for iron castings are usually made of sand, using clay-water or resin bonds. Sea coal is generally added to the molding sand; it expands and cokes in response to the heat from the solidifying casting, and resists penetration of molten metal into the mold. Cores are often coated to produce a smoother finish than can be obtained from sand. The particle size of the refractories used in the coating is much finer than that of the sand. Venting of mold cores used for cast iron is important to avoid non-fill and misrun.

Gray Irons

GRAY IRON ALLOYS are primarily iron-carbon-silicon ternary alloys. Most gray irons are produced with 3.0 to 3.5% carbon levels and 1.8 to 2.4% silicon levels. Gray irons are characterized by the presence of most of the contained carbon as flakes of free graphite in the as-cast iron. Gray iron has the lowest casting temperature, the least shrinkage, and the best castability of all ferrous casting alloys.

Principles of Solidification

A section from the Fe-C-Si equilibrium phase diagram at the 2.5% Si level is shown in Fig. 3. The diagram shows that cast iron undergoes a eutectic solidification reaction and a eutectoid solidification reaction on cooling from liquid to solid. An approximate way of converting cast iron composition to that of the simple Fe-C binary eutectic is through the use of the concept of the carbon equivalent (CE). In its most simple form, the carbon equivalent is:

$$CE = \%C + (\%Si/3)$$

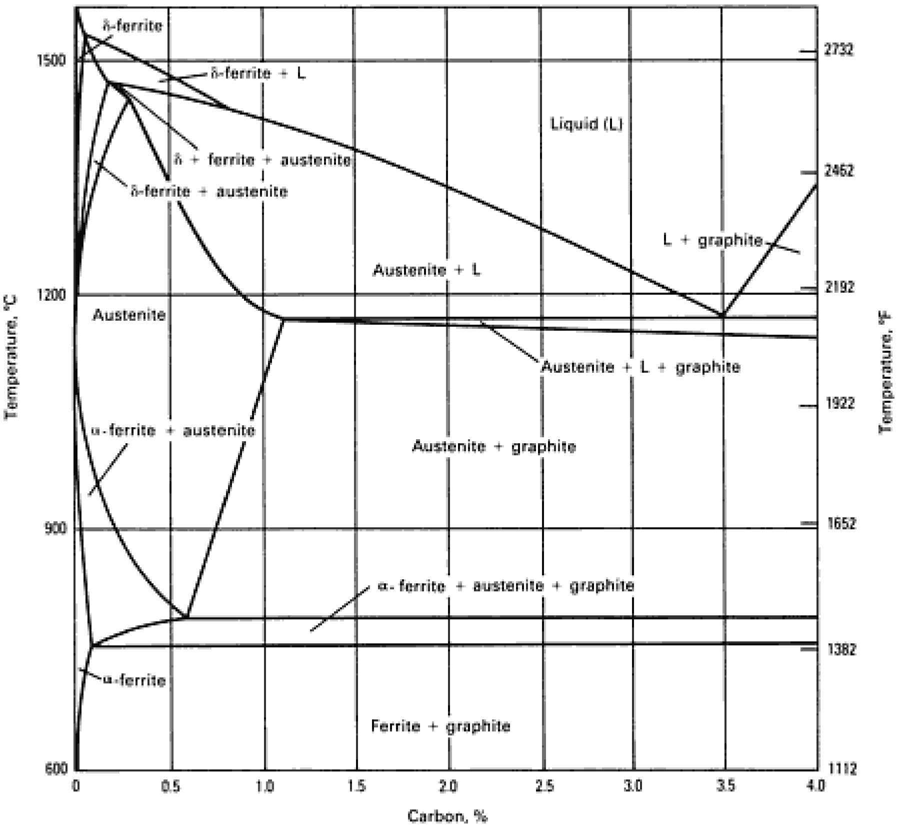


Fig. 3 Iron-carbon phase diagram at 2.5% Si

For irons containing appreciable amounts of phosphorous, the carbon equivalent is:

$$CE = \%C + [(\%Si + \%P) + 3]$$

Based on these relationships and the equilibrium phase diagrams, an iron having a carbon equivalent of 4.3 is a eutectic cast iron. Most cast irons are hypoeutectic, meaning that their carbon equivalent is less than 4.3. The carbon equivalent can be determined by chemical analysis or thermal analysis, the latter of which can be carried out rapidly on the foundry floor during production.

In cast iron, minor elements that must be controlled for proper solidification and performance include phosphorus, manganese, and sulfur. Phosphorous improves fluidity but increases shrinkage in cast iron, because the phosphorous forms a eutectic that shrinks on solidification. Sulfur affects the nucleation of graphite and must be balanced with manganese additions to promote the formation of manganese sulfide inclusions. Trace elements can also have significant effects on casting structure and quality, and these are summarized in Table 1.

Table 1 Effects, levels, and sources of some trace elements in gray iron

Element	Trace level, %	Effects	Sources
Aluminum	≤0.03	Promotes hydrogen pinhole defects, especially when using green sand molds and at levels above 0.005%. Neutralizes nitrogen	Deliberate addition, ferrous alloys, inoculants, scrap contaminated with aluminum components
Antimony	≤0.02	Promotes pearlite. Addition of 0.01% reduces the amount of ferrite sometimes found adjacent to cored surfaces.	Vitreous enameled scrap, steel scrap, white metal bearing shells, deliberate addition
Arsenic	≤0.05	Promotes pearlite. Addition of 0.05% reduces the amount of ferrite sometimes found adjacent to cored surfaces.	Pig iron, steel scrap
Bismuth	≤0.02	Promotes carbides and undesirable graphite forms that reduce tensile properties	Deliberate addition, bismuth-containing molds and core coatings
Boron	≤0.01	Promotes carbides, particularly in light-section parts. Effects become significant above about 0.001%.	Deliberate addition, vitreous enameled scrap
Chromium	≤0.2	Promotes chill in thin sections	Alloy steel, chromium plate, some refined pig iron
Copper	≤0.3	Trace amounts have no significant effect and can be ignored.	Copper wire, nonferrous alloys, steel scrap, some refined pig iron
Hydrogen	≤ 0.0004	Produces subsurface pinholes and (less often) fissures or gross blowing through a section. Mild chill promoter. Promotes inverse chill when insufficient manganese is present. Promotes coarse graphite	Damp refractories, mold materials, and additions
Lead	≤0.005	Results in Widmanstätten and "spiky" graphite, especially in heavy sections with high hydrogen. Can reduce tensile strength 50% at low levels (≥0.0004%). Promotes pearlite	Some vitreous enamels, paints, free-cutting steels, nonferrous alloys, terne plate, white metal, solder, some pig irons
Molybdenum	≤0.05	Promotes pearlite	Some refined pig iron, steel scrap
Nickel	≤0.01	Trace amounts have no major effect and can be ignored.	Refined pig iron, steel scrap
Nitrogen	≤0.02	Compacts graphite and increases strength. Promotes pearlite. Increases chill. Can cause pinhole and fissure defects. Can be neutralized by aluminum or titanium	Coke, carburizers, mold and core binders, some ferroalloys, steel scrap
Tellurium	≤0.003	Not usually found, but a potent carbide former	Free-cutting brasses, mold and core coatings, deliberate addition

Tin	≤0.15	Strong pearlite promoter; sometimes deliberately added to promote pearlitic structures	Solder, steel scrap, nonferrous alloys, refined pig iron, deliberate addition
Titanium	≤0.15	Promotes undercooled graphite. Promotes hydrogen pinholing when aluminum is present. Combines with nitrogen to neutralize its effects	Some pig irons, steel scrap, some vitreous enamels and pains, deliberate addition
Tungsten	≤0.05	Promotes pearlite	Tool steel
Vanadium	≤0.08	Forms carbides; promotes pearlite	Steel scrap; some pig irons

As most gray irons are hypoeutectic, their solidification behavior can be illustrated with the help of the simplified ternary eutectic diagram taken at 2% silicon shown in Fig. 4. At temperatures above point 1, the iron is entirely molten. As the temperature falls and the liquidus line is crossed, primary freezing begins with the formation of proeutectic austenite dendrites. These dendrites grow and new dendrites form as the temperature drops through the primary freezing range, between points 1 and 2. Dendrite size is governed by the carbon equivalent of the melt and the freezing rate (the faster the freezing rate and the higher the carbon content, the finer the dendrites).

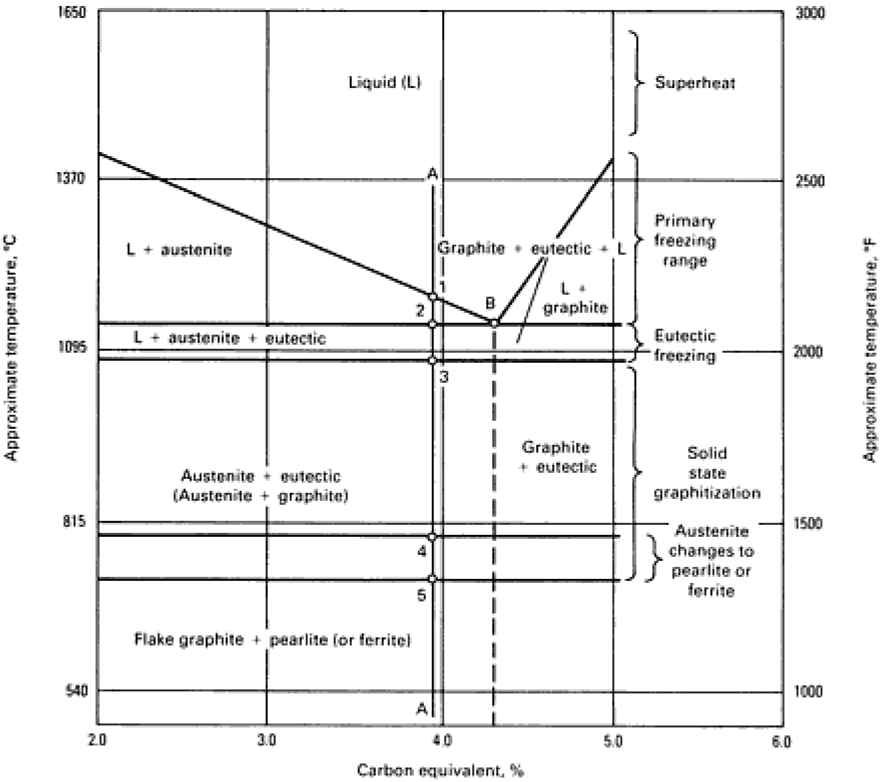

1650
1370
1095
815
540
3000
2500
2000
1500
1000
Approximate temperature, °C
Approximate temperature, °F
Liquid (L)
Superheat
A
L + austenite
Graphite + eutectic + L
Primary freezing range
1
2
B
L + graphite
L + austenite + eutectic
Eutectic freezing
3
Graphite + eutectic
Solid state graphitization
Austenite + eutectic (Austenite + graphite)
Austenite changes to pearlite or ferrite
4
5
Flake graphite + pearlite (or ferrite)
A
2.0
3.0
4.0
5.0
6.0
Carbon equivalent, %

Fig. 4 Simplified iron-carbon-silicon phase diagram at 2% Si

During the formation of the austenite dendrites, carbon is rejected into the remaining liquid. The carbon content of the liquid increases until it reaches the eutectic composition of 4.3%. At this composition, the remaining liquid transforms into two solids, between points 2 and 3. The type of solid depends on whether the transformation is stable or metastable. In the stable transformation, graphite and austenite form. In the metastable transformation, iron carbide and austenite form. At point 3, all of the liquid is solid, and any further transformations take place in the solid state. As the solid cools from point 3 to point 4, carbon diffuses from the high carbon austenite to the graphite flakes, and at point 4 the austenite transforms to pearlite (a mixture of iron carbide and ferrite) or to a mixture of ferrite and pearlite.

Graphite Morphology. Five types of graphite, known as A to E, are found in gray iron. How the shape, size, amount, and distribution of graphite flakes influence mechanical and physical properties of gray irons is described in detail in the Section "Cast Irons" in this Handbook.

Cementite. If the cooling rate of the liquid at the eutectic temperature is very rapid, as in thin sections, the eutectic liquid will undercool substantially and solidify rapidly. If the solidification rate is too rapid, graphite will not have time to form, and the metastable form of the eutectic, cementite (iron carbide, Fe_3C), will form. Cementite is hard and brittle, and generally is not desired. When a casting that has solidified at a rapid rate and formed cementite is fractured, the fracture is white. The structure is therefore known as "white iron" or "chill iron." The tendency to form white iron is enhanced by the addition of carbide formers such as chromium to the melt, while the formation of graphite is enhanced by the addition of graphitizers such as silicon or copper. One way of estimating the tendency of a melt to form white iron is to pour a wedge-shaped bar, such as that shown in Fig. 5, to allow it to solidify, and then to fracture the bar and examine the amount of the structure that solidifies with the white structure. At cooling rates between that producing a white iron structure and that producing a gray iron structure, a mixture of eutectic structures called a "mottled" structure (Fig. 6) is formed.

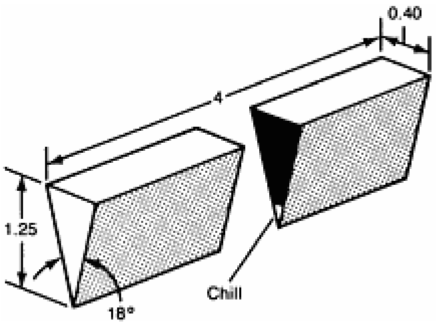


Fig. 5 Standard W2 wedge block used for measuring depth of chill (ASTM A 367). Dimensions are given in inches.

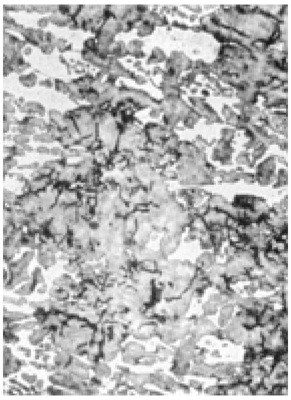


Fig. 6 Mottled cast iron etched using 4% picral. The white phase is eutectic carbide. 50×

Matrix Phases. The steel matrix consists of ferrite or pearlite or a mixture of both. Ferrite is soft and contains little carbon, and its formation is promoted by graphitizers such as silicon and by a slow cooling rate. Pearlite is a eutectoid mixture of ferrite and cementite, which forms in alternate thin plates. Pearlite is harder and less ductile than ferrite, and its hardness and tensile strength depend primarily on the spacing of the plates. Higher values are found in pearlite with the fine interlamellar spacing associated with more rapid cooling rates and/or alloying.

In cast irons containing more than 0.2% phosphorous, the iron phosphide eutectic may form at cell boundaries, where it has a concave triangular shape, as shown in Fig. 7. This phase lowers properties. Other phases that may occur include manganese sulfide inclusions, shown in Fig. 8, and carbides or carbonitrides.

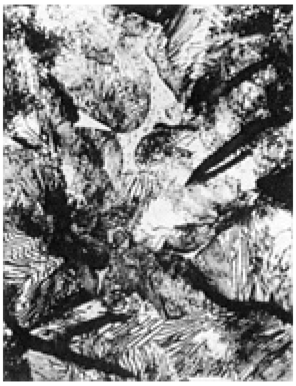


Fig. 7 Steadite in gray cast iron. Etched using 2% nital. 400×

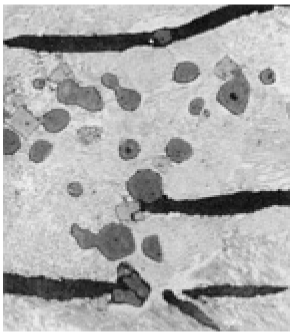


Fig. 8 Manganese sulfide (dark gray, rounded) and titanium carbonitride (light gray, angular) inclusions. Etched using 2% nital. 500×

Melting Practice

The essential purpose of melting is to produce molten iron of the desired composition and temperature. For gray iron, this can be accomplished with various types of melting equipment. Cupolas and induction furnaces tend to be the types most commonly found in the gray iron foundry. The cupola was traditionally the major source of molten iron, but gradual acceptance of electric melting has reduced its dominance. Gray iron can be melted with a single furnace or a combination of furnaces (duplexing).

Regardless of the type of furnace used, the basic melting process is a physical transformation from solid to liquid rather than a complex reduction or oxidation reaction. Therefore, the composition of all the materials charged into the furnace determines the composition of the slag/iron mixture.

Charge materials for cupolas are described in the article "Melting Methods" in this Section.

Charge Materials for Induction Furnaces. Compositional control of gray iron is greater in induction furnaces than cupolas because of the reduced oxidation losses during melting and the elimination of coke as fuel. The composition of the metallic charge materials is directly related to the final composition of the iron. Therefore, accurate weights and analysis of charge materials are required for good compositional control. Typical charge materials include steel scrap, cast iron scrap, foundry returns, ferrosilicon, and carbon. Pig iron is rarely used because of cost, although it does offer advantages in terms of purity. The type of scrap employed will depend on economics. The elimination of coke from the charge also reduces the sulfur absorbed by the iron; therefore, resulfurization is often desirable in electrically melted gray iron.

A typical charge for class 30 iron of 4.20 carbon equivalent (CE) is:

Steel scrap	**41.3%**
Gray iron borings	10.0%
Foundry returns	45.0%
Carbon	1.7%
50% ferrosilicon	2.0%

The CE can readily be adjusted to any desired level by balancing steel scrap content and additions of carbon and ferrosilicon. Alloying additions are absorbed rapidly at 90 to 95% recovery, and the ease of meeting chemical and mechanical specifications, including those difficult or impractical in cupola melting, is valuable. Carbon additions are made with pelletized petroleum coke of controlled grain size to give high and reproducible recoveries. Because little sulfur is introduced in induction melting, the sulfur content of the melted iron is considerably lower than that from a cupola, and thus less manganese is required for balance with sulfur.

Desulfurization Methods

Excess free sulfur in gray iron increases chill depth, decreases fluidity, and decreases the effectiveness of inoculation. Several successful desulfurization techniques have been developed in the search for methods of obtaining low-sulfur base irons. Calcium carbide has proved to be the most effective desulfurizing agent for low sulfurs. Lime is also an effective desulfurizing agent, but it requires more volume, time, and agitation. Small percentages of fluorspar and various salts improve the desulfurizing effectiveness of lime.

Metal stirring or agitation is essential for promoting optimum desulfurization. The following stirring methods have been found to be effective:

- Carbide is injected with inert gas through graphite or refractory lances that supply the carbide and simultaneously stir the melt.
- Inert gas is bubbled through a porous plug in the bottom of a ladle, with desulfurizing agent fed onto the surface with a vibrating feeder.
- The shaking ladle system places a ladle of iron in a gyrating shaking mechanism that stirs in the desulfurizing agent.
- The refractory stirrer system rotates a refractory paddle in the bath, stirring the carbide or lime into contact with the iron.

With any of these stirring methods, additions of 0.50 to 1.0% CaC_2 have desulfurized irons of 0.07 to 0.10% S, as melted, down to a final 0.01 to 0.02% S. A temperature loss of 30 to 55 °C (50 to 100 °F) can be expected. Lime alone or with various salts can be used as the desulfurizing agent. The efficiency is lower than that with carbide, but there are fewer environmental problems.

Injection and porous plug desulfurizing systems can be either batch type, treating individual ladles, or a continuous system, with the cupola stream flowing through a special forehearth outfitted with a porous plug and a carbide feed (or injection lance). The spent carbide or lime is raked off or overflows, and the desulfurized metal flows continuously into the holder or duplex electric furnace. Disposal of the carbide slag requires attention to safety and environmental considerations.

Inoculation

To control the properties of cast iron, it is necessary to control the formation of the graphite flakes (the eutectic reaction), and the formation of the steel matrix (the eutectoid reaction). Controlling the eutectic reaction means controlling the amount of undercooling that the eutectic liquid undergoes. This is accomplished by the practice of inoculation.

Inoculation is the late addition of ferrosilicon alloys to molten iron to nucleate the graphite. Ferrosilicon alloys usually contain either approximately 50% silicon or 75% silicon and act as carriers for the nucleating elements, which include calcium, barium, titanium, and rare earths, such as cerium. Graphite itself may also be added as an inoculant; the best graphite (such as furnace electrodes) is highly crystalline in structure. Graphite is usually added in addition to ferrosilicon. The amount of ferrosilicon added is not especially large, which means that the chemical composition of a melt is changed only slightly by inoculation. Thus two nearly identical melt compositions can produce entirely different cast structures depending on whether or not an inoculant has been added to the melt.

Types of Inoculants. Inoculants may be divided into performance categories as follows: standard, intermediate, high potency, and stabilizing. The performance of the first three categories is shown in Fig. 9. (Stabilizing inoculants are added to control both the eutectic and the eutectoid reactions.) As the potency of the inoculant increases, so does its cost. Adding extra inoculant is not recommended because the effect of the inoculant drops with increasing additions, and inoculants form dross that can lead to inclusion defects in the casting.

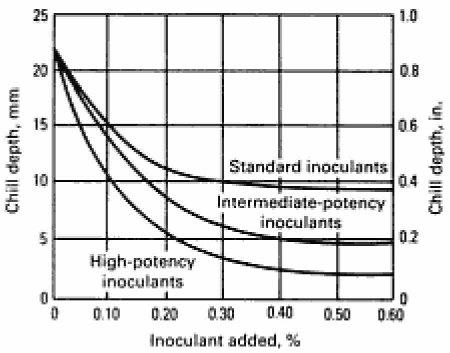


Fig. 9 General classification of inoculants showing chill reduction in iron with carbon equivalence of 4.0

Addition Methods. Inoculants may be added to the melt in a number of different ways. Ladle inoculation is common; in this, the alloy is added to the stream of metal as it flows from the transfer ladle to the pouring ladle. Stream inoculation is the addition of the inoculant to the pouring stream as the metal enters the mold. Mold inoculation involves placing the inoculant in the mold, usually at the base of the sprue. These last three methods are referred to as "late inoculation" and are used to counteract the phenomenon of "fade," in which the inoculant loses effectiveness with an increase in time from addition to time of solidification. The effect of inoculation is best within five minutes; if iron is held more than 15 to 30 min after inoculation and before pouring, there is usually no effect at all.

Alloying

Alloying elements may be added to cast iron to obtain specific properties that are not obtainable without alloy additions. Alloying and inoculation are not the same process and should not be confused, although alloying can affect choice of inoculation practice. Common alloying elements for gray iron include chromium, copper, nickel, molybdenum, and tin. The effects of these additions are as follows:

- Chromium additions of 0.5 to 0.75% increase the strength of gray iron by increasing the pearlite content. Chromium is also a chill promoter.
- Copper additions in the range of 0.25 to 0.5% increase tensile properties, again by promoting the formation of a pearlite matrix. Copper also acts as a graphitizer.
- Nickel additions of up to 2% cause a minor increase in properties. Nickel is also a graphitizer.
- Molybdenum in additions of 0.25 to 0.75% has a significant impact on the strength of gray iron as a

matrix strengthener and a graphite flake refiner.

- Tin in the range of 0.025 to 0.1% stabilizes pearlite.

When higher amounts of alloying elements are added, the product is known as "alloyed cast iron" or "high-alloy cast iron."

The choice of alloying element and the amount to add depends on the base iron composition, the part being made, and the properties desired. Parts produced from different base irons and alloy additions can have the same tensile properties and performance in service, although other properties may vary. Note also that because the matrix of gray iron is steel, it is possible to heat treat gray iron to adjust its properties from those produced as-cast. However, as the graphite flakes act as stress concentration points, gray iron has little ductility.

Alloying addition practices vary considerably, depending on the method of melting, the composition and product form of the alloy being added, the amount of iron being alloyed (the entire charge or only portions of the charge), and the ladling practice in the specific foundry.

In cupola melting, nickel, copper, chromium, and molybdenum are added to molten metal during or after tapping, rather than being added to the cupola charge. If the ladle that receives the molten metal at the spout will pour the castings without a transfer, the alloying metal may be added to the stream at the spout. This practice generally provides reasonably thorough mixing, although the exact amount of iron tapped into the receiving ladle is sometimes difficult to control. A more common practice is to add the alloying metals to the stream from the receiving ladle (or forehearth, if used) as it is transferred to the pouring ladle, because it may not be desirable to alloy all of the metal in the receiving ladle or forehearth. The amount of mixing obtained by adding to the stream is usually sufficient, although to obtain more thorough mixing the alloyed metal is sometimes poured from the transfer ladle to another transfer ladle.

The practices described above may also be employed if the melting is done in an arc or induction furnace. However, if the entire charge of an arc or induction furnace is to be alloyed, the alloying metals may be added to the furnace, usually just a few minutes prior to tapping. Because of the stirring action in these furnaces (particularly in an induction furnace), losses of the alloying metals from oxidation can be excessive if too much time elapses between making the additions and tapping.

An advantage of adding the alloying metals to the charge in the furnace is stability of temperature. When alloying metals are added cold to the ladle after tapping, there can be a significant decrease in temperature. The amount of temperature drop increases with the amount of cold metal added. Ladle additions of cold metal that total more than 3% are not recommended.

Alloying metal should never be placed in an empty ladle; the bottom of the ladle should be covered with at least 1 in. of molten metal before any alloying metal is added. Preferably, alloy is added as a small amount at one time. Alloy additions come in the form of shot, scrap, or granulated ferroalloys.

Pouring

Metal temperature, cleanliness, and delivery technique are the essential variables to be controlled when pouring gray iron. Removal of slag and dross from the liquid iron surface reduces the possibility of inclusion-type defects. A variety of metal-pouring techniques are employed in the gray iron foundry. Each technique should enable the operator to maintain a constant flow of metal sufficient to keep the gating system full of metal until the pour is completed.

The molten iron should possess sufficient superheat to enable the cavity to be completely filled with iron without the formation of temperature-related defects. Superheat is the differential between the molten iron temperature and the liquidus temperature. The fluidity of the iron is directly proportional to the amount of superheat contained in the iron. Therefore, thinner sections that require greater fluidity for successful casting also require more superheat than thicker sections. The liquidus of gray iron is determined by the composition of the iron. For hypoeutectic irons, the liquidus is inversely proportional to the CE of the iron. Therefore, the higher-strength irons with lower CE require higher pouring temperatures to maintain the necessary level of superheat. Table 2 lists the typical pouring temperatures required for the various classes of gray iron.

Table 2 Typical pouring temperatures for some classes of gray iron

Class	Approximate liquidus temperature		Pouring temperature							
			Small castings				**Large castings**			
			Thin sections		**Thick sections**		**Thin sections**		**Thick sections**	
	°C	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**	**°C**	**°F**
30	1150	2100	1400	2550	1370	2500	1345	2450	1315	2400
35	1175	2150	1425	2600	1400	2550	1370	2500	1345	2450
40	1200	2190	1450	2640	1420	2590	1395	2540	1365	2490

Iron containing insufficient superheat can lead to partially filled cavities, misruns, blowholes, and chill. An excess of superheat can lead to shrinkage, metal penetration, veining, and scabbing. The amount of superheat required will vary for individual castings, and some experimentation will be required to determine the optimum pouring temperature for each casting.

Molding

Although gray iron can be produced by using most of the molding processes described in the article "Molding Methods" in this Section, green sand molding is the most widely used technique. Gray iron expands slightly because of the formation of graphite during eutectic solidification. This is most pronounced in higher-CE irons, in which more graphite is precipitated. This expansion stresses the molding material, causing an enlargement of the mold cavity if the sand is insufficiently compacted. This can lead to shrinkage defects. Therefore, it is important when producing gray iron castings that the mold hardness be sufficient to withstand the eutectic expansion of the gray iron.

Gating and Risering

Because graphite expands on solidification, risers on gray iron castings are usually small (in some castings and grades of iron, it is possible to omit them entirely). Gate and riser removal are easy, as the low ductility of the material means that it is necessary only to notch the gate attachments, and the gating and risers fall off in shakeout. (Those that do not break off while moving down the cooling conveyor are easily broken off with hammers.) While the expansion of graphite at the end of solidification means that risers may be small, it also causes penetration defects in castings if there is no liquid path to a riser. When the graphite expands, it pushes any remaining liquid ahead of it. If the section has frozen off from the rest of the casting, and there is no liquid communication with the riser, liquid may be pushed through the casting wall in hot spots (such as concave corners that trap heat) into the mold. If no such path exists, the expansion of the graphite will distort the casting dimensions, causing section sizes to swell. This is often blamed on movement of the mold-wall; in reality, it is a casting design problem. Graphite expansion decreases as the phosphorous level increases, so high phosphorous irons require larger risers but are less prone to mold wall movement and metal penetration problems.

Ductile Irons

DUCTILE IRON, also called nodular iron or spheroidal graphite (SG) iron, has a chemical composition very similar to that of gray iron. However, in ductile iron, the graphite solidifies in the form of tiny spheres (Fig. 10). As this figure shows, the steel matrix can be varied in ductile iron just as it can be in gray iron. Because the spheres do not act as stress raisers, as do the flakes in gray iron, ductile iron has high ductility similar to that of steel. Because the graphite lowers the melting point from that of steel, ductile iron is, in many ways, a low-cost, lower melting point steel.

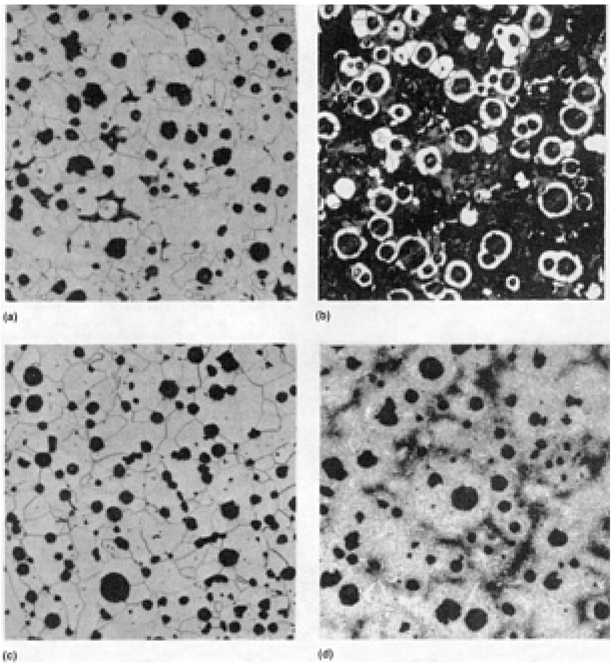


Fig. 10 Microstructures of ductile iron. (a) As-cast ferritic. (b) As-cast pearlitic, hardness 255 HB. (c) Ferritic, annealed 3 h at 700 °C (1290 °F). (d) Pearlitic ductile iron, oil-quenched and tempered to 255 HB. All etched in 2% nital. 100×

Ductile iron is made by treating low-sulfur liquid cast iron with an additive containing magnesium. This treatment is known as nodulizing or nodularization. The melt is usually inoculated just before or during casting with a silicon-containing alloy. To successfully make ductile iron, it is necessary to exercise more control than is customary in making gray iron over the melting and treatment of the liquid iron. Charge materials must be selected to minimize trace elements such as antimony, titanium, bismuth, and zirconium, which can have a deleterious effect on the nodulizing process (see Table 3). In addition, the sulfur content must be reduced below 0.02% before attempting the nodulizing treatment. This is normally accomplished in a separate desulfurization step in which the liquid iron is treated with lime or calcium carbide. The desulfurization step is crucial in the production of ductile iron, as excess sulfur reacts with the nodulizing element magnesium and destroys its effect.

Table 3 Summary of the effects of various elements found in ductile irons

Element	Typical amount	Maximum for matrix		Positive effects	Deleterious effects
		Ferrite	**Pearlite**		
Spheroidizing elements					
Mg	0.02-0.08%	Sufficient to ensure spheroidal graphite		Lowers sulfur and oxygen contents; causes graphite to form spheroids	Excess promotes carbides
Rare earths	0-0.30%	About 0.035%	About 0.035%	Promotes nodule count and quality in combination with magnesium; neutralizes subversive elements	Excess promotes carbides in thin sections and chunky graphite in heavy sections
Ca	Not detected	Essentially insoluble	Essentially insoluble	Increases nodule count and improves nodule quality; optimizes inoculation	Excess promotes carbides
Ba	Not detected	Essentially insoluble	Essentially insoluble	Increases nodule count; optimizes inoculation	. . .
Primary elements					
C	3.00-4.00%	3.00-4.00%	3.00-4.00%	Present as spheroids or carbides	Excess results in graphite formation
Si	1.80-3.00%	1.80-3.00%	1.80-2.75%	Promotes graphitization during solidification and matrix formation	Hardens and strengthens ferrite; increases nil-ductility temperatures
P	About 0.02%	0.035% max	0.05% max	Kept as low as possible	Forms intercellular carbide network; promotes pearlite
S	0.01-0.02%	0.02% max	0.02% max	Combines with magnesium and rare earths	Limits efficiency of magnesium treatment process
Mn	0.00-1.20%	0.20%	0.80% max	Promotes pearlite in as-cast and normalized iron	Intercellular carbides when over 0.70%
Alloying elements					
Ni	0.01-2.00%	As low as possible for as-cast	To specification	Employed for hardenability (e.g., pearlitic)	. . .
Mo	0.01-0.75%	0.03% max	To specification	Promotes hardenability	Excess promotes intercellular carbides

Cu	0.01-0.90%	0.03% max	To specification	Promotes pearlitic hardenability	No significant effect on nodule count or quality
Tramp elements					
Te	<0.005%	0.02% max	0.02% max	Used to control pinholes	Promotes spheroid degeneration in absence of rare earths
Pb	. . .	0.002% max	0.002% max	Kept as low as possible	Promotes intercellular flake graphite
Ti	<0.07%	0.03% max	0.07% max	Kept as low as possible	Promotes vermicular graphite
Al	0.003-0.06%	0.05% max	0.05% max	Used in ferroalloys to suppress chill	Promotes vermicular graphite effect--greater in heavy sections; promotes pinholes
Sb	<0.005%	0.001% max	0.001% max	Strong pearlite former; counteracts chunky graphite in heavy sections	Nodule degeneration at high levels when rare earths are not present
Bi	<0.01%	0.002% max	0.002% max	Increases nodule count and quality when rare earths are present	Promotes vermicular graphite in absence of rare earths
Zr	<0.01%	0.10% max	0.10 max	Kept as low as possible	Promotes vermicular graphite
Carbide and pearlite forming elements					
Cr	0.02-0.15%	0.04% max	0.10 max	Very powerful carbide former	Carbides resistant to annealing
B	<0.0005%	0.002% max	0.002% max	Kept as low as possible	Forms intercellular carbides that resist annealing
Sn	<0.10%	0.01% max	0.08% max	Very potent pearlite former	At <0.10%, forms intercellular structure with flake graphite
As	0.01% max	0.02% max	0.05% max	About 0.08% required for pearlitic matrix	. . .
V	<0.04%	0.04% max	0.05% max	Forms very stable carbides	Retards annealing
Gaseous elements					
O	<0.005%	About 0.003%	About 0.003%	Kept as low as possible	Combines with magnesium

H	0.0002-0.0015%	About 0.0003%	About 0.0003%	Kept as low as possible	Promotes centerline carbides and inverse chill; promotes pinholes
N	. . .	. . .	. . .	Kept as low as possible	Mild carbide forming tendency; may contribute to porosity

Ductile iron castings are produced using the same molding methods associated with gray irons. Small amounts of alloying elements may be added to promote pearlite, carbides, and hardenability (see Table 3). Special properties, such as resistance to heat, corrosion, or oxidation, can be achieved by alloying with nickel (20%), chromium (up to 5%), and silicon (up to 6%). As with gray irons, these more highly alloyed materials are referred to as alloyed cast irons or high-alloy irons.

Charge Materials and Melting Practice

The spheroidal form of graphite that characterizes ductile iron is usually produced by a magnesium content of about 0.04 to 0.06% (it may be lower if the sulfur content of the liquid metal is below 0.015%). Magnesium is a highly reactive element at molten iron temperatures, combining readily with oxygen and sulfur. For magnesium economy and metal cleanliness, the sulfur content of the iron to be treated should be low (<0.02%). This is readily achieved in an electric furnace by melting charges based on steel scrap or special-quality pig iron supplied for ductile iron production, together with ductile iron returned scrap. Low sulfur content can also be achieved by melting in a basic cupola, but acid cupola melted iron has a higher sulfur content and normally needs to be desulfurized before treatment by continuous or batch desulfurization in a ladle or special vessel. Treatment of acid cupola melted iron with magnesium without prior desulfurization is not recommended, because the iron consumes more magnesium and produces excessive magnesium sulfide slag that is difficult to remove thoroughly and may lead to dross defects in castings.

Magnesium Treatment

To achieve the spherical shape of the graphite, a nodulizing treatment is necessary. This is carried out by adding magnesium to the melt. Rare earth elements such as cerium can also be used, but magnesium is used most commonly. Magnesium may be introduced as pure magnesium metal or alloyed in ferrosilicon containing 3 to 10% Mg or nickel-base nodulizers containing 4 to 16% Mg. The magnesium additions can be added to the ladle during filling or by plunging. Regardless of the method for adding magnesium, the aim is to recover as much magnesium as possible.

The reaction between metallic magnesium and molten iron is violent. The magnesium is vaporized and burns vigorously in air, forming magnesium oxide. Enclosed reaction vessels, such as those shown in Fig. 11 and 12, are needed. The violence of the reaction may be reduced by alloying the magnesium with nickel or ferrosilicon. Magnesium alloys may also be added in the mold, as a ferrosilicon-magnesium alloy placed in the runner system. Magnesium recovery averages around 50%. As stated above, the residual magnesium content required in the metal to produce spheroidal graphite is usually in the range of 0.04 to 0.06%.

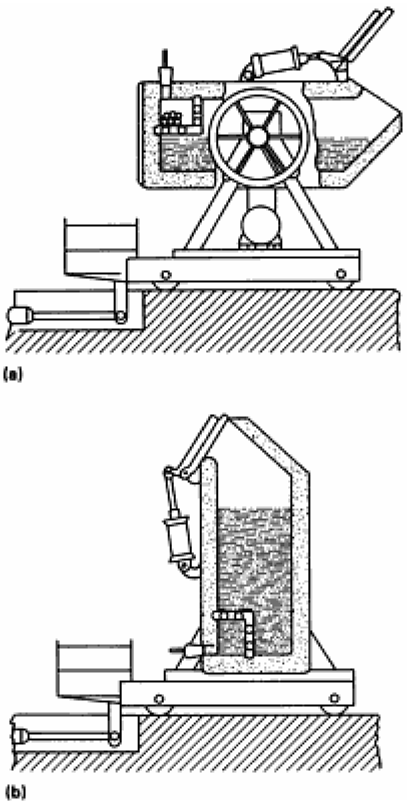


Fig. 11 Schematic of the Fischer converter. (a) Vessel in filling position. (b) Vessel in treating position

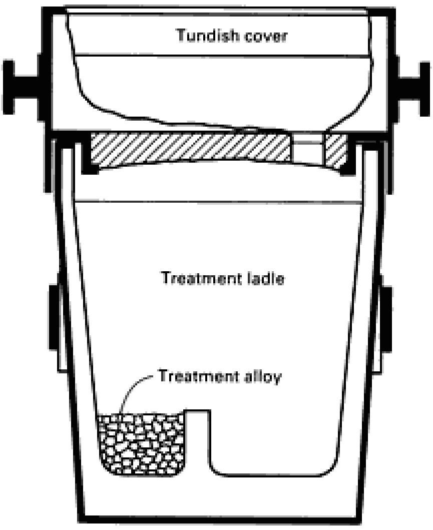


Fig. 12 Treatment ladle with tundish cover used in the magnesium treatment of ductile iron

Inoculation

Following magnesium treatment, the iron usually is given a final inoculation to produce nuclei for the graphite nodules. Inoculation is commonly carried out in the ladle using a granular inoculant like commercial ferrosilicon containing 75% Si or proprietary inoculation alloys containing 60 to 80% Si. The amount of inoculant usually ranges from about 0.25 to 1.0%. The inoculant can be added during reladling, stirred into the metal, placed on the bottom of the ladle before filling, or plunged in a refractory bell. Effective mixing/stirring of the inoculant is necessary during addition. Metal must be poured as soon after magnesium treatment and inoculation as possible to avoid fade of both the magnesium and the inoculant.

Gating, Pouring, and Risering

Gating Systems. Ductile iron contains magnesium, and oxidation of this element, together with silicon, can give rise to small inclusions and dross in both the ladle and the gating system. This dross must not enter the casting where it can cause laps, rough surfaces, or pinholes. Other recommendations include:

- Metal held in the ladle must be skimmed clean. The use of teapot ladles is advisable.
- Magnesium content should be kept to a minimum, preferably less than 0.06%.
- A gating system of adequate size should be used, designed to achieve rapid mold filling with minimum turbulence of metal.
- A slightly pressurized gating ratio is desirable. For example, suitable ratios of cross sections of sprue-runner-ingate may be 4:8:3 to ensure a short filling time and a full sprue during casting.
- Ingates should be placed in the drag, as near the bottom of the casting as possible.
- A ceramic filter in the gating system removes small slag inclusions and assists smooth metal flow. Ceramic filters reduce dross defects and improve the mechanical properties of the iron.

Pouring Temperature. Excessive temperature gradients in the casting and pouring of cold metal are undesirable and can promote carbide formation in thin sections and casting extremities. These can be avoided by pouring at not less than 1315 °C (2400 °F) for castings of 25 mm (1 in.) section and above, by pouring at up to 1425 °C (2600 °F) for castings of 6 mm ($\frac{1}{4}$ in.) section, and by modifying the gating system to include such features as flowoffs and runner bar extensions.

Solidification and Feeding (Risering). The change from flake to nodular graphite is accompanied by important differences in solidification behavior. In hypereutectic irons, graphite segregation and flotation occur more easily than in gray iron. Such segregation can aggravate dross problems and give rise to local high-carbon regions that adversely affect mechanical properties and the appearance of machined surfaces. During solidification, the precipitation of graphite in a nodular form causes ductile iron castings to expand to a greater degree and with more force than gray iron. Consequently, ductile iron castings require more rigid molds and more attention to feeding.

In green sand molds, in particular, ductile iron castings are likely to be oversized compared with the pattern and compared with gray iron castings. It is necessary to make dense molds. Flasks require good weighting and clamping, especially for larger castings, and they may need internal bars. The use of chemically hardened or dry sand molds is a great advantage, provided that they are adequately cured.

It is sometimes possible to make sound ductile iron castings of simple shapes without the use of risers by taking advantage of graphite expansion, which occurs during eutectic solidification. The requirements are:

- A strong, well-compacted, chemically bonded sand mold contained in a rigid molding flask
- A CE of about 4.3 and a carbon content of about 3.6%
- A low casting temperature, preferably below 1350 °C (2460 °F)
- A gating system and running speed to minimize temperature gradients developed in the mold

Nevertheless, for most purposes, ductile iron castings will require the use of risers to ensure fully sound castings, even in rigid molds. Risers are usually larger than for gray iron. The principles of directional solidification should be employed in casting design with regard to the placement of gates and the locations of risers.

Because ductile iron has substantial ductility, gate and riser removal is more difficult than in gray iron. In some instances, abrasive cutting wheels must be used to avoid damage to the castings.

Microstructures and Heat Treatments

Graphite. The amount and form of the graphite in ductile iron are determined during solidification and are not changed during subsequent treatment. The ductility of the iron and its properties depend on the nodularity of graphite, as shown in Fig. 13. Figure 14 shows microstructures containing estimated graphite nodularities of 99, 80, and 50%. Nodule count is also important. Structures showing four different levels of nodule count are shown in Fig. 15.

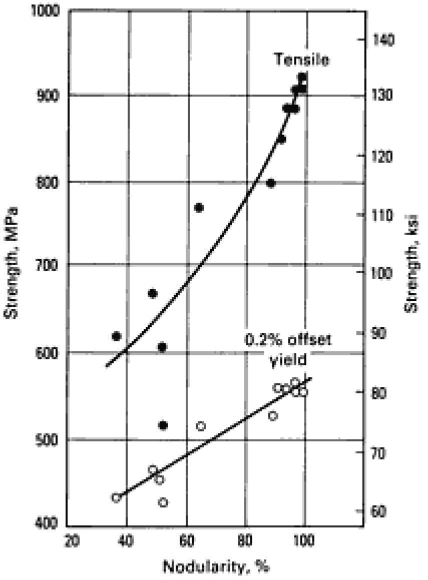


Fig. 13 Tensile and yield strength of ductile iron vs. visually assessed nodularity

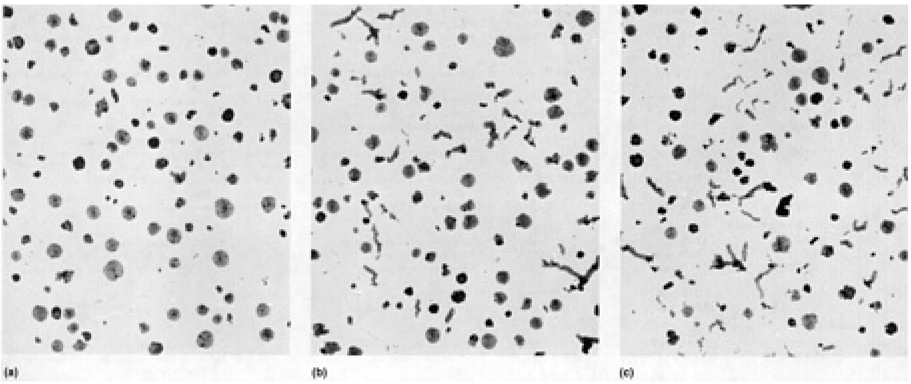


Fig. 14 Microstructure of ductile irons of varying degrees of nodularity. (a) 99% nodularity. (b) 80% nodularity. (c) 50% nodularity. All unetched. 36×

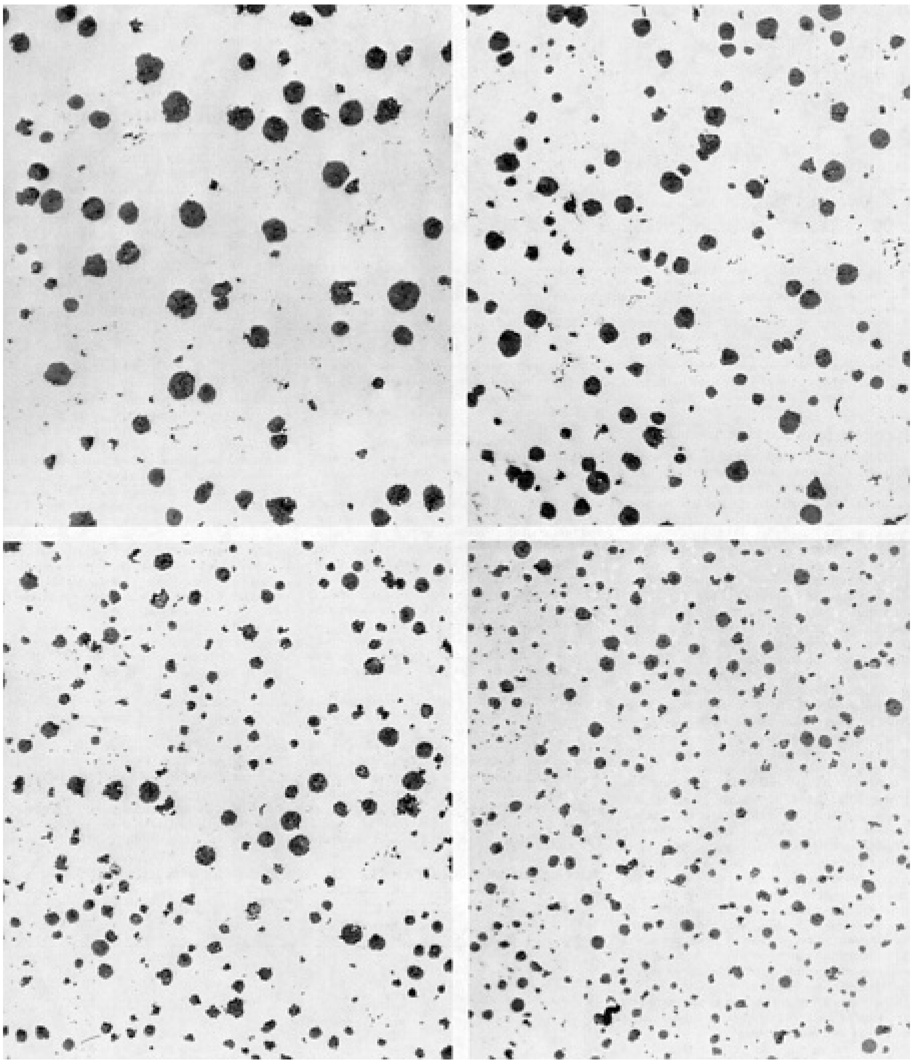


Fig. 15 Series of micrographs depicting increasing nodularity in ductile irons. Upper left: 50 nodules per 10 mm square. Upper right: 100 nodules per 10 mm square. Lower left: 150 nodules per 10 mm square. Lower right: 200 nodules per 10 mm square. As-polished. 100×

Carbides. The carbide content must be controlled to improve machinability and to allow sufficient carbon to be present in the matrix for effective heat treatment. As listed in Table 3, chromium, vanadium, and boron are all carbide promoters. Manganese may accentuate the carbide-stabilizing effects of these elements, especially in heavy sections in which segregation promotes grain-boundary carbides. These elements are controlled by careful selection of metallic raw materials for charging/melting.

Matrix Structures and Heat Treatments. The principal factor in determining the different grades of ductile iron is the structure of the matrix. As-cast, the structure consists of varying proportions of pearlite and ferrite, and, as in steel, the strength and hardness of the iron increases as the pearlite content increases. The matrix structure (but not the graphite morphology, nodularity, or nodule count) can be altered by heat treatment. Annealing will produce a fully ferritic matrix, and normalizing can produce a fully pearlitic matrix. Very high values of strength and ductility can be obtained by an austempering heat treatment.

Heat treatment of ductile iron is similar to heat treatment of steel. The most important heat treatments and their purposes are:

- Stress relief, a low-temperature treatment to reduce or relieve internal stresses that form from strains induced during solidification
- Annealing, a high-temperature heat treatment that improves ductility and toughness by dissolving

carbides

- Normalizing to improve strength with some ductility
- Tempering to increase the strength
- Austempering to provide high strength, good wear resistance, and some ductility

Heat treatments, which involve heating above the upper critical temperature and converting the matrix into austenite, followed by controlled cooling and holding at temperature cycles, produce a variety of microstructures. The structures can be divided into two broad classes: (a) those where the iron matrix is the stable ferrite structure and (b) those where the iron matrix is the metastable austenite structure. In the first category are normalizing, annealing, and tempering. The second category includes austempering, which produces austempered ductile iron (ADI). ADI is a unique cast iron material having properties distinctly different from those of ductile irons given stable matrix heat treatments. It is produced by heating ductile iron into the austenite phase range, above 815 to 925 °C (1500 to 1700 °F), depending on the composition of the iron; holding until the transformation of the matrix to austenite is complete; cooling to a temperature above that where martensite (a very hard matrix) can form; and holding at that temperature until the matrix transforms into a structure consisting of acicular ferrite and carbon-enriched austenite, as shown in Fig. 16. The two different matrix structures shown yield different properties (as described in the caption to Fig. 16) and are produced by using different transformation temperatures.

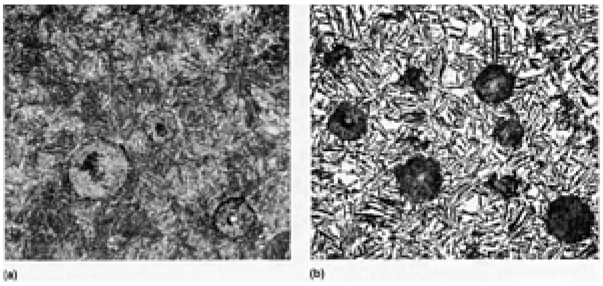


Fig. 16 Micrographs of ductile iron treated at different austempering temperatures. (a) Ductile iron austempered at 260 °C (500 °F) exhibits a fine acicular structure with the following properties: tensile strength, 1585 MPa (230 ksi); yield strength, 1380 MPa (200 ksi); elongation, 3%; unnotched impact strength, 54 J (40 ft · lbf); hardness, 475 HB. (b) Same iron as in (a), austempered at 370 °C (700 °F), exhibits a coarse acicular structure with the following properties: tensile strength, 1035 MPa (150 ksi); yield strength, 825 MPa (120 ksi); elongation, 11%; unnotched impact strength, 130 J (95 ft · lbf); hardness, 321 HB. Both etched with 3% nital. 300×

Compacted Graphite Irons

COMPACTED GRAPHITE (CG) IRONS have a solidification structure (graphite morphology) and properties intermediate between those of gray iron and those of ductile iron. The graphite in CG iron is in the form of short, blunt flakes that are interconnected (CG graphite morphology is illustrated in the Section "Cast Irons" in this Handbook). The procedures and production techniques used for ductile iron (regarding raw materials, melting furnaces, desulfurization, and post inoculation treatments) are also used for production of CG iron.

Chemical Composition and Melt Treatment

Chemical Composition. The range of acceptable carbon and silicon contents for the production of CG iron is rather wide, as shown in Fig. 17. Nevertheless, the optimum CE must be selected as a function of section thickness, in order to avoid carbon flotation when CE is too high or excessive chilling tendency when CE is too low. The manganese content can vary between 0.1 and 0.6%, depending on whether a ferritic or pearlitic structure is desired. Phosphorus content should be kept below 0.06% in order to obtain maximum ductility from the matrix. The initial sulfur level should be below 0.025%, although techniques for producing CG iron from base irons with higher sulfur levels are available.

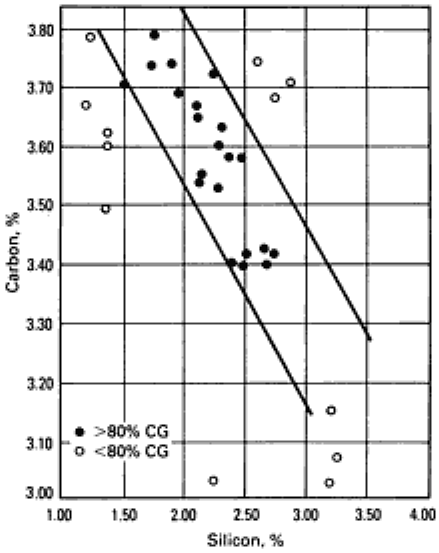


Fig. 17 Optimum range for carbon and silicon contents for compacted graphite (CG) iron

Melt Treatment. The unique graphite morphology is produced by melt treatment with magnesium or rare earth elements, much like ductile iron. However, in CG iron, the structure is produced by adding less of these elements than would be added for ductile iron, or by adding them in combination with other elements such as titanium or aluminum to balance the elements which promote spheroidal graphite formation. Compositions of typical treatment alloys used in the production of CG iron are listed in Table 4. As in ductile iron, control of the sulfur content is especially important. Excessive sulfur produces a flake graphite structure at the surface and in thin sections, while too little sulfur produces a spheroidal (nodular) graphite. Because the chilling tendency of CG iron is higher than that of either gray or ductile iron, consideration of the section size in determining melt treatment is of the greatest importance.

Table 4 Nominal compositions of typical treatment alloys for compacted graphite iron

Alloy number	Composition, %								
	Compactizing elements					**Anticompactizing elements**		**Neutral elements**	
	Mg	**Ce**	**La**	**TRE$^{(a)}$**	**Ca**	**Ti**	**Al**	**Si**	**Fe**
1	5	. . .	. . .	. . .	1	. . .	<1.2	45	bal
2	5	0.3	. . .	0.3	<1	9	<1.5	52	bal
3	5	0.3	. . .	0.3	4.5	9	1.2	50	bal
4	. . .	24	14.4	48	7.5	. . .	4.3	33.2	bal
5	. . .	30	50	80	. . .	. . .	. . .	. . .	bal
6	. . .	16	80	96	. . .	. . .	. . .	. . .	bal

7	. . .	2.9	26.5	29.4	0.63	. . .	0.13	30.5	bal
8	3.7	0.8	0.5	1.7	1.05	. . .	0.88	45.3	bal
9	4.3	0.7	1.8	2.9	0.66	. . .	0.9	45.3	bal

(a) TRE, total rare-earth elements

Structure / Property Relationships

As the properties of CG iron that differentiate it from gray and ductile iron depend on the shape of the graphite, deviations from that shape affect the properties. The matrix structure, which also controls properties, can be controlled by adding elements such as copper, tin, and molybdenum to change the matrix from ferrite to pearlite. In addition, heat treatments to produce the stable (ferritic or pearlitic) matrix can be carried out to adjust the properties.

Compared to gray irons, CG irons have higher tensile strength at the same carbon equivalents, higher ductility and toughness, and less section sensitivity in heavy sections. Compared to ductile irons, CG irons have a lower coefficient of thermal expansion, higher thermal conductivity, higher damping capacity, and better castability. Compacted graphite iron may also be alloyed to obtain special properties for a given service application, for example, heat or wear resistance. Although not widely used in the United States, CG irons are used for automotive engine components in Europe.

Malleable Irons

MALLEABLE IRON is a form of cast iron in which the graphite is precipitated from the metastable iron carbide (white iron) phase during a lengthy two-stage heat treatment. The graphite, called "temper carbon," takes the form of irregularly shaped nodules in a low-carbon steel matrix. As a result of the shape of the graphite, malleable iron possesses good ductility and toughness. Information regarding graphite morphology, properties, and heat treatments for malleable irons can be found in the Section "Cast Irons" in this Handbook.

Chemical Composition, Melting, and Molding

Chemical Composition. To produce malleable iron it is necessary to first produce white iron as the solidification structure. This is accomplished by limiting the carbon and silicon content to levels below those used for gray or ductile iron. Carbon contents generally range between 2.0 and 2.9%, and silicon is between 0.9 and 1.9%. Higher levels generally produce a mixture of flake graphite and white iron known as "mottled iron." Sulfur and manganese contents are balanced so that the sulfur combines with the manganese, and only a minimal amount of excess manganese is present in the iron. Because castability and ease of heat treatment are improved at the higher levels of carbon and silicon, it is common for malleable foundries to choose iron compositions that would normally produce a mottled structure and deliberately add an element that promotes the formation of the metastable eutectic, Fe_3C, on solidification. Bismuth at the level of 0.01% or tellurium at the level 0.004% is commonly used as a ladle addition. Other carbide stabilizers, such as chromium, are undesirable, as they interfere with carbide decomposition during heat treatment. Specific additions may be made to promote the transformation of iron carbide into graphite. These include small amounts of boron (0.001%) and aluminum (0.005%) as ladle additions.

Melting Practice. Foundries having low tonnage requirements generally charge, melt down, refine, and superheat the iron in batches. This practice is commonly referred to as "cold" melting. Such installations use electric induction, electric arc, or air (reverberatory) furnaces for melting a properly proportioned charge of white iron returns, scrap iron and steel, pig iron, and ferroalloys. Air furnaces are fired with powdered coal, natural gas, or oil. The charge is laid in the hearth of the furnace and is melted by passing the flame over it. After the melt has been superheated, a sample has been chemically analyzed, and the bath has been corrected as necessary by alloy additions, the melt is tapped and transferred by ladle to molds. The tapping temperature, usually 1475 to 1600 °C (2700 to 2900 °F), depends on the composition of the iron, the fluidity of the iron required to fill the thinnest sections to be cast, and the facilities for metal transfer. Ordinarily, only one heat per day is melted in batch air-furnace operations.

Where larger tonnages are needed or where a continuous supply of molten iron is required to pour conveyorized molding lines, electric melting furnaces or duplexing systems are employed. With electric installations, either multiple batch heats can be arc melted, or line-frequency coreless induction furnaces can be used. The choice of an electric melting system for a malleable iron foundry involves the same considerations as for a gray iron foundry. In coreless induction melting, a portion of the superheated melt is periodically tapped and replenished at once with new charge.

Cupola furnaces are also used to melt iron without duplexing for some malleable castings, especially pipe fittings. Furnace linings are generally either silica or superduty refractories. Metal superheating temperatures range from 1475 to 1600 °C (2700 to 2900 °F), depending on the necessity for reladling, the composition of the iron, and the section thickness of the castings to be produced.

Duplexed malleable iron is first melted in cupolas or in arc or induction furnaces, and then is refined in arc, induction, or air furnaces. Usually, primary melting units are operated to provide molten metal for duplexing at relatively low temperatures (1425 to 1500 °C, or 2600 to 2750 °F), because primary melters generally are not efficient superheaters. Final superheating temperatures vary from 1475 to 1600 °C (2700 to 2900 °F), depending on the needs of individual foundries. Minor corrections in composition can be made in the duplexing furnace, but basic process control is generally accomplished in the primary melting unit.

Molding. The requirement that the entire casting solidify with a white iron structure means that the cooling rate during solidification must be rather rapid. This is usually accomplished without difficulty in green sand molds, provided that casting sections are not too heavy. Thick sections, over 100 mm (4 in.), solidify too slowly to produce the white iron structure and are not candidates for malleable iron. However, thin section castings that might solidify white because of the rapid cooling rate their geometry produces are ideal for malleable iron.

High-Alloy White Irons

HIGH-ALLOY WHITE CAST IRONS are an important group of materials whose production must be considered separately from that of ordinary types of cast irons. In these cast iron alloys, the alloy content is well above 4%, and consequently these alloys cannot be produced by ladle additions to irons of otherwise standard compositions. They are usually produced in foundries that are specially equipped for the heat treatment and other thermal processing unique to the production of highly alloyed irons. These iron alloys are most often melted in electric furnaces, specifically electric arc furnaces and induction furnaces, in which precise control of composition and temperature can be achieved.

The high-alloy white irons consist of two major groups. The nickel-chromium white irons, commonly referred to as Ni-Hards, contain 3 to 7% Ni and about 1.5 to 11% Cr. The second group, the high-chromium white irons, contains 11 to 28% Cr and 0.5 to 3.5% Mo. Both groups are used for abrasion-resistant applications.

Melting Practice

Furnaces. Although nickel-chromium irons can be melted in a cupola, both nickel-chromium and high-chromium white irons are most commonly melted in electric arc or induction melting furnaces. High-alloy white irons are readily made in acid-, neutral-, or basic-lined electric furnaces. They are normally dead melted, and there is usually no reason to use oxygen lancing except as a means of slightly reducing carbon content. Despite rapid refractory wear due to chromium-bearing slag, acid linings are generally more economical than basic linings. Very little adjustment to slag composition is necessary in acid melting, which is used for the majority of current production.

Normal charge materials are various kinds of steel scrap, foundry returns, or returns of similar alloy from service. For foundries that lack the facilities for rapid melt analysis, it may be necessary to select steel scrap rather carefully to control residual levels of alloying elements that affect austenite retention (e.g., manganese and copper).

Chromium is obtained in the form of high-carbon ferrochrome and is generally added near the end of the heat to avoid excessive oxidation losses. Carbon is obtained from electrode graphite, petroleum coke, and other sources. Pig iron is also used to carburize the melt and can be an additional source of silicon. Silicon and manganese are added as ferroalloys.

Molybdenum is usually added as ferromolybdenum; however, with arc furnaces, molybdenum oxide briquettes may be used. Sulfur is limited to 0.06%, and phosphorus is kept to 0.10%, as specified by ASTM A 532.

Melt Temperature. High superheating temperatures have not been necessary when melting in induction furnaces that have good stirring action, and a final temperature of 1480 °C (2700 °F) is usually adequate for thick-section castings. Final temperatures of up to 1565 °C (2850 °F) are commonly used in arc furnace practice to ensure homogeneity of the bath composition and to accelerate the solution of carbon, added after meltdown, and late alloy additions.

Pouring Practice

High pouring temperatures aggravate shrinkage under feeder heads and other hot spots and can lead to microshrinkage and coarse dendritic structures. Careful control of pouring temperature is particularly important in the consistent production of thick-section castings. Low pouring temperatures are necessary to avoid shrinkage defects and prevent problems such as metal penetration and burned-on sand. Low pouring temperatures are also effective in controlling dendrite size and the coarseness of the eutectic carbide structure.

The eutectic temperature for the various nickel-chromium iron grades is approximately 1200 °C (2190 °F), and solidification generally begins at 1200 to 1280 °C (2190 to 2340 °F), depending on composition. For high-chromium iron grades, the eutectic temperature ranges from 1230 to 1270 °C (2245 to 2315 °F), and solidification generally begins at temperatures up to 1350 °C (2460 °F), depending on composition. When selecting a pouring temperature, common rules apply. Pouring temperatures are seldom lower than 100 °C (180 °F) above the liquidus temperature. Higher pouring temperatures may be necessary when pouring smaller castings. Of course, casting configurations must be considered when selecting optimum pouring temperatures.

Molds, Patterns, and Casting Design

Molds must be rigid to minimize shrinkage defects. Molds may be made of green sand, dry sand, oil sand, or steel casting sand. Air-setting and thermal-setting resin sands are also commonly used. Because white irons are subject to hot tearing, cores should break down readily.

Nickel-chromium irons may also be chill cast in permanent molds. The chill-cast microstructures develop higher hardness, strength, and impact toughness than the sand-cast structures because of the finer carbides. Whenever practical, the wearing faces of the casting should be cast against a chill to improve abrasion resistance and toughness.

Sand molds may be made either of green sand or of dry sand, oil sand, or steel casting sand. Air-setting and thermal-setting resin sands are also commonly used. Molds must be rigid to minimize shrinkage defects.

White irons are subject to hot tearing unless suitable precautions are taken. When castings are extracted from the mold, they are occasionally found to be cracked. Stresses large enough to cause fracture can arise when either the mold or the cores are excessively strong and there is inadequate mold or core breakdown to allow normal thermal contraction with cooling. Large cores, such as those used in pump volutes, and even small cores used to form bolt holes can cause cracking of this type.

Shrinkage allowance for nickel-chromium irons is 13 to 21 mm/m ($\frac{5}{32}$ to $\frac{1}{4}$ in./ft); for high-chromium irons the shrinkage allowance is 18 to 21 mm/m ($\frac{7}{32}$ to $\frac{1}{4}$ in./ft). The actual pattern allowance depends on the choice of alloy and the geometry of the casting. Patterns should employ generous radii and avoid sharp section changes to avoid initiating cracking upon solidification and subsequent cooling.

High-alloy white irons exhibit relatively high liquid-to-solid shrinkage, so large gates and risers are required for feeding. Special consideration should be given to the design of end gates and to the positioning of risers so they can be readily removed. Risers are often notched or necked down to facilitate removal by impact.

Shakeout Practice

The shakeout practice is probably the most critical step in the successful production of high-chromium iron castings. A frequent cause of high residual stresses and of cracking is the common practice of extracting castings from the mold at too high a temperature. Cooling all the way to room temperature in the mold is desirable and can be a requirement to avoid cracking, especially if martensite forms during the last stages of cooling. This precaution is mandatory in heavy-section castings to be used in the as-cast condition where the desired mold-cooled structure is a mixture of austenite and martensite.

Thin-section castings and castings having simple shapes are less susceptible to stresses and are often removed from the mold once the castings have reached black heat. With these castings, slow cooling favors higher as-cast hardness.

Steels

STEEL CASTINGS comprise approximately 10% of the overall casting market. These castings are used where high performance is required. Because steel has such a high melting point, steel castings pose particular problems not found in lower-melting point alloys. Most steel is arc melted, and the use of mold coatings is always required to prevent metal penetration defects. Because steel is easily welded, very large and complex components can be made by welding together steel castings. As in cast iron, the properties of steel castings can be controlled extensively by controlling the alloy content and the heat treatment of the castings. Heat treatment of steel castings follows the same rules used for heat treating any steel of similar composition. A protective atmosphere must be used during heat treatment to control the carbon content at the surface of the casting.

General Considerations for Steel Castings

Steel foundries are especially concerned with melt practice to control the chemistry and properties of the castings produced. Molding practice is also important. Because of steel's high melting temperature, it is normally poured into sand molds. The high temperatures required encourage reactions between the metal and the sand. For this reason, non-silica sands such as zircon, chromite, and olivine are frequently used in steel foundries, either for the entire mold, or as facing sands. When silica sand is used, it is usually coated with a mold wash (coating), containing magnesite, zircon, or mullite, or finely divided silica. The high pouring temperatures generate large quantities of gas from the volatile components (moisture and core resins) in the mold, so mold venting is especially important. High-carbon steels, such as those used for railroad car wheels, may be poured in graphite molds.

The composition of the mold must be controlled because the atmosphere for the casting during cooling in the mold can cause surface carburization or decarburization. If the mold atmosphere becomes oxidizing, which can happen easily, even in molds containing sea coal, liquid iron oxide can form on the surface during solidification. This iron oxide then dissolves the sand at the casting surface, forming fayalite ($FeSiO_4$) that produces a rough and unacceptable surface on the casting. Coatings are extensively used in steel foundries on both molds and cores to protect the casting from penetration defects. Gating systems must be carefully designed to fill the mold rapidly but with as little turbulence as possible to avoid reoxidation of the molten metal and inclusion formation. Because of steel's high melting temperature, radiation from the metal that is filling the mold can heat the cope surface of the casting cavity, causing expansion and spalling that lead to defects known as scabs or rattails. This can be avoided by filling the mold rapidly.

Because steel castings possess substantially more ductility than gray iron, gate and riser removal is usually done using abrasive cut-off wheels or oxyacetylene or other gas torches. Wire electrical discharge machining (EDM) may also be used to remove gates. Grinding wheels usually are used to remove gate stubs, but EDM may also be used. After heat treatment, the castings may be finished by shot blasting and machining.

Carbon Steels

The simplest steels in terms of composition are the plain carbon steels. These materials contain carbon and from 0.25 to 0.80% Si, 0.50 to 1.0% Mn, and traces of deoxidizing elements such as aluminum, titanium, and zirconium. They are classified into three main groups according to their carbon contents:

- Less than 0.20% C are low-carbon steels
- From 0.20 to 0.50% C are medium-carbon steels
- Greater than 0.50% C are high-carbon steels

The carbon content selected has a great effect on the mechanical properties of cast plain-carbon steel as does the heat treatment selected (see the article "Steel Castings" in the Section "Carbon and Alloy Steels" in this Handbook). Section size also affects properties, as properties depend on the cooling rate during solidification, and heavy sections solidify more slowly than thin sections.

Carbon steels generally are melted in electric arc furnaces; melting practice is discussed in the article "Melting Methods" in this Section. While melting generally follows the melt practice used in steel mills, tapping temperatures must be higher to assure that the molten metal will fill the mold. Another difference between the melt practice used in steel mills and that used in foundries is that steel poured in the foundry is always fully deoxidized.

Because plain carbon steels solidify with a fairly small mushy region, they are prone to the formation of centerline porosity, and risers used with them pipe deeply. Centerline shrink can be cured by tapering the casting section, with the small end of the taper away from the riser. The size of the riser can be reduced with the use of exothermic riser sleeves that keep the riser liquid while it provides feed metal for the casting. Carbon steels are especially sensitive to reoxidation inclusions formed during pouring and mold filling. These inclusions tend to float to the top of the solidifying casting and are often found during machining operations in a layer just beneath the cope surface of the casting. They can be controlled by the use of filters in the runner system, by counter-gravity casting techniques, or a combination of both.

Alloy Steels

Steels are alloyed to obtain specific properties, such as corrosion resistance; improved properties at high or low temperatures; or to produce a specific response to heat treatment. Alloyed steels may be either "low-alloy" or "high-alloy," depending on the amounts of alloying elements they contain. While standard designations for wrought and cast grades of alloy steels refer to the same amounts of alloying elements, alloy steels differ from wrought compositions in that they will normally contain 0.30 to 0.65% Si and 0.50 to 1.00% Mn unless otherwise specified. Alloy steels have lower melting points than carbon steels of the same carbon content and solidify in a somewhat more mushy manner; this can be compensated for in riser design. Melting and deoxidation practices for low-alloy steels are the same as those for plain carbon steel. Depending on the alloying element, alloying may be carried out in the original charge (if the element is not oxidized during the refining step), at the end of the melt just before tapping, or in the ladle. Low-alloy steels are generally melted in arc furnaces, but high-alloy steels may be melted in induction furnaces. Vacuum melting is rarely used for alloy steels, but these steels may be vacuum degassed.

An important consideration in low-alloy steels is the control of the response of the microstructure to cooling rate during solidification and heat treatment. Since the surface of the casting cools much faster than the interior, it may have a different microstructure than the interior, a situation that may decrease casting properties. The principal method of hardening carbon and low-alloy steels is to quench the steel from the austenitizing temperature and then temper the steel to produce the desired microstructure. However, steels vary in their response to quench rate, depending on their composition. Figure 18 schematically shows the cooling curves for the center and surface of a steel section superimposed on the continuous cooling transformation diagram. The curve labeled "50% martensite" intersects the pearlite area briefly, showing that half the mass is transformed to pearlite, and the remainder is transformed to martensite. By adding the proper alloying elements, the entire casting can be made to transform to pearlite, avoiding formation to martensite.

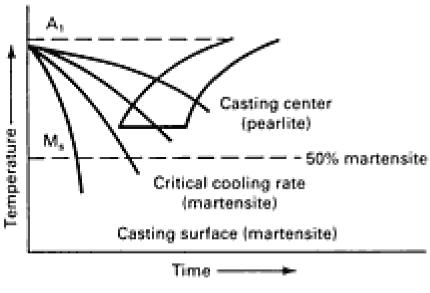

A_1
Casting center (pearlite)
M_s
50% martensite
Critical cooling rate (martensite)
Casting surface (martensite)
Temperature
Time

Fig. 18 Difference in cooling rates at the surface and center of a steel casting and the resulting microstructures obtained

Low-alloy steels contain up to 8% alloying elements. They generally fall into the following families:

- *Carbon-manganese steels*, containing 0.20 to 0.50% carbon and 1.00 to 1.90% manganese. These steels have excellent properties that are obtained with a simple normalizing heat treatment.
- *Manganese-molybdenum steels,* which have higher hardenability than carbon steels and better properties at elevated temperatures. These steels contain 0.20 to 0.50% C and are available in two grades, one containing 1.0 to 1.30% Mn and 0.10 to 0.30% Mo, and another containing 1.35 to 1.75% Mn and 0.25 to 0.55% Mo.
- *Manganese-nickel-chromium-molybdenum steels* that are used because their high hardenability makes it possible to produce castings having sections up to 125 mm (5 in.) thick with a fully tempered martensitic structure.
- *Nickel steels,* which contain up to 4% Ni and have high mechanical properties.
- *Nickel-chromium-molybdenum steels,* which are used when high hardenability and elevated temperature properties are desired.

As the composition of the steel varies, its response to cooling rate also varies, which, as noted, is a primary reason for alloying. This response to the effect of cooling rate also influences the weldability of alloy steels. As the alloying content increases, it is necessary to slow the cooling rate to avoid formation of martensite. This is done by preheating and sometimes postheating the weld zone.

High-alloy steels include stainless steels used for corrosion and heat resistance and high-manganese (austenitic) steels used for wear resistance. Foundry practice for stainless steels is similar to that for carbon and low-alloys steels. Compositions and properties of cast stainless steels can be found in the Section "Stainless Steels" in this Handbook.

High manganese steels are most commonly produced in electric arc furnaces using a basic melting practice. They are also induction melted. Typical charge materials include carbon and manganese steel scrap, high-carbon ferromanganese, ferrosilicon, and silicon-manganese. Alloying elements such as chromium, molybdenum, and vanadium are usually added as ferroalloys, while elements such as nickel are used in a nearly pure metallic state. Deoxidation of the steel is accomplished with aluminum prior to pouring. In the case of most castings, the pouring temperature is regulated to less than 1470 °C (2680 °F) to prevent an excessively coarse grain size and minimize chemical segregation and other related casting defects. In casting high manganese steels, care must be taken in selecting mold and core coatings, as these steels react with silica sands and other refractories to produce MnO, a highly fluid liquid oxide which causes severe metal penetration. As a result, sand castings are produced with olivine rather than silica sand to prevent mold-metal reaction. Compositions and properties of high manganese steel castings can be found in the article "Wear-Resistant Austenitic Manganese Steels" contained in the Section "Carbon and Alloys Steels" in this Handbook.

Aluminum Alloys

ALUMINUM CASTINGS are primarily used because of their light weight and corrosion resistance. There are a wide variety of aluminum alloys, developed for both properties and the casting method employed. Foundry alloys may be divided into two groups: those most suitable for gravity casting by any process and those used in pressure die casting. A finer distinction is made between alloys suitable for permanent mold application and those for other gravity processes. In general, the most alloy-versatile processes (that is, those in which the largest number of alloys can be used) are those in which the mold collapse accompanies pouring and solidification. The least forgiving processes, which require special consideration in alloy selection, are more rigid or permanent mold processes. The least alloy-versatile casting process based on process requirements is pressure die casting, in which more than the usual measures of castability apply. The process demands a high level of fluidity, hot strength, hot tear resistance, and die soldering resistance. Chemical compositions of aluminum casting alloys are given in the Section "Aluminum and Aluminum Alloys" in this Handbook (see Table 2 in the article "Chemical Compositions and International Designations"). Aluminum alloys are cast in all casting processes, including green sand, dry sand, composite mold, plaster mold, investment casting, permanent mold, counter-gravity low-pressure casting, and pressure die casting.

Melting and Metal Treatment

Aluminum and aluminum alloys can be melted in a variety of ways. In routine use are coreless and channel induction furnaces, crucible and open-hearth reverberatory furnaces (fired by natural gas or fuel oil), and electric resistance and electric radiation furnaces. The nature of the furnace charge may range from prealloyed ingot of high quality to charges made up exclusively from low-grade scrap. However, even under optimum melting pouring conditions, molten aluminum is susceptible to three types of degradation:

- With time at temperature, adsorption of hydrogen results in increased dissolved hydrogen in the melt.
- With time at temperature, oxidation of the melt occurs.
- Loss of alloying elements

Dissolved Hydrogen. Hydrogen is easily adsorbed by molten aluminum. Unfortunately, the solubility of hydrogen in molten aluminum alloys is substantially greater than in solid aluminum (Fig. 1). When the aluminum alloy solidifies, hydrogen is driven out of solution, exaggerating and enlarging shrinkage porosity, with accompanying loss in mechanical properties (Fig. 2). Sources of hydrogen may include wet charges and damp melting tools, but the primary source of hydrogen is ambient humidity. Because little can be done to prevent hydrogen pickup during melting, hydrogen must be removed from the melt before pouring. The most common method used is bubbling dry nitrogen or argon through the melt. Rotary degassing units, as described and illustrated in the article "Melting Methods" in this Section (see Fig. 17 of that article), are particularly effective. These units may be inserted into melting crucibles for use. The use of chlorine gas is especially effective in removing hydrogen; however, environmental and safety considerations generally preclude its use in production.

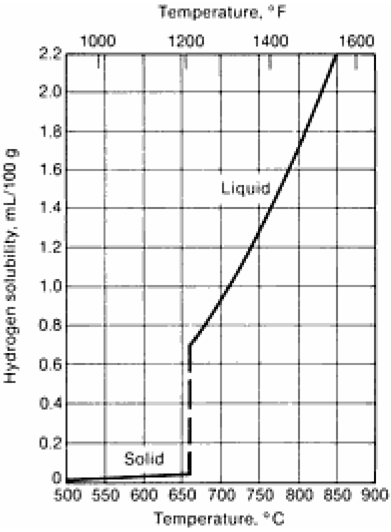


Fig. 1 Solubility of hydrogen in aluminum at 1 atm hydrogen pressure

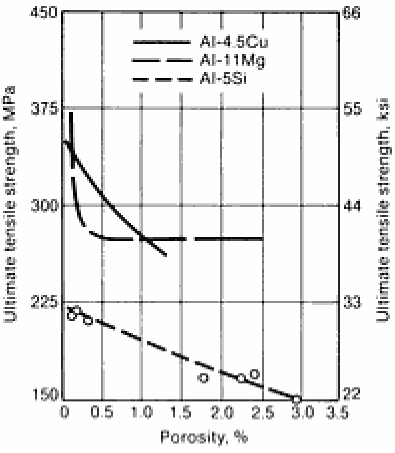


Fig. 2 Ultimate tensile strength versus hydrogen porosity for sand cast bars of three aluminum alloys

Measurement of the amount of hydrogen dissolved in the melt has historically been done using a reduced pressure test in which a sample of molten aluminum is poured into a small steel cup and allowed to solidify in a vacuum chamber. Solidification is observed; the degree of evolution of bubbles during solidification indicates the amount of hydrogen present. Subsequent sectioning of the solidified sample and inspection of the size of the pores formed is also used. Unfortunately, these methods are inaccurate and are heavily influenced by the presence in the melt of oxide particles that act as nuclei for the hydrogen bubbles. The preferred way to test for dissolved hydrogen is to use instruments specifically designed to show hydrogen by liquid extraction techniques.

Oxidation of the Melt. Aluminum forms a very stable oxide that forms instantaneously on the surface of the melt. The rate of oxidation increases with temperature and the presence of certain alloying elements, such as magnesium and beryllium. While the oxide film that forms on the surface of an aluminum melt is self-limiting if the surface of the melt is not disturbed, any turbulence will mix the oxide film into the bulk of the melt and create a fresh surface for the formation of more oxide. The oxide films and oxide inclusions that result are especially detrimental to the performance of aluminum castings. Turbulence may be induced during alloying operations, molten metal transfer, or pouring and mold filling.

Oxide particles in the melt serve as nuclei for the formation of shrinkage and gas porosity. In the absence of oxide inclusions, porosity and microporosity are substantially reduced. This is an especially important consideration in aluminum casting alloys, as they often have very large liquidus-to-solidus spreads and freeze in a mushy manner making feeding very difficult.

Oxide films in the casting form planes of weakness that nucleate failure under load. Much of the scatter in mechanical properties of cast aluminum alloys results directly from the presence of these films. When they are absent, the scatter is reduced, and the reproducibility of casting properties surpasses that of forgings. The films are not normally visible during radiographic inspection and must be prevented rather than found and repaired.

Oxides are controlled by using covering fluxes during melting. These fluxes are usually magnesium chloride salts, and they float on the melt surface. They must be removed from the surface of the melt periodically. Suspended oxide inclusions are removed from large melters by passing the melt through a filter bed. In smaller operations, the oxides are removed by placing filters in the gating system.

Prevention of the formation of oxide films in the casting requires that the metal enter the mold cavity in a non-turbulent manner. As this is not possible using gravity pouring methods for most castings, because the head height of sprues accelerates the metal to speeds where turbulent flow takes place, counter-gravity or liquid-level mold filling techniques must be used. While filters slow the velocity of the metal, they rarely slow it enough to prevent oxidation. Mold cavities must be filled from the bottom, and the sequence in which different levels in the casting fill must be carefully planned to avoid "waterfalling," the dropping of liquid metal from a higher to a lower level in the mold, and the resulting oxidation of newly created metal surface. By filling the mold from the bottom, the oxide layer on the top of the liquid metal will rise to the top of the cope surface and flow into top risers where it will not harm the casting.

Loss of Alloying Elements. Many aluminum casting alloys contain elements such as magnesium that react with oxygen over time. If molten metal is held too long, these elements will be lost, and the chemical composition of the resulting casting will not be within specification. Other alloying elements, such as zinc, may have low vapor pressures and evaporate from the surface of the bath.

Structure Control

Aluminum alloy melts are commonly treated to produce the desired metallurgical microstructure during solidification. Both nucleation of the primary dendrites and the form of the eutectic are controlled.

Dendrite Arm Spacing. In all commercial processes, solidification takes place through the formation of dendrites in the liquid solution (see the article "Solidification of Metals and Alloys" in this Section). The cells contained within the dendrite structure correspond to the dimensions separating the arms of primary dendrites and are controlled for a given composition exclusively by solidification rate. Dendrite cell sizes on the order of 25 μm produce optimum mechanical properties in aluminum castings.

Grain Structure. A fine, equiaxed structure is normally preferred in aluminum alloys, as such a structure improves feeding, the response to heat treatment, and mechanical properties. Grain refinement is accomplished through the addition of small amounts of master alloys (grain refiners) of titanium (containing 3 to 10% Ti) or titanium and boron (containing 0.2 to 1% boron and titanium-to-boron ratios of from 5 to 50). The effect is dramatic, as shown in Fig. 3. Care must be taken in using these grain refiners to avoid excessive superheating of the melt. In addition, because titanium oxidizes easily, the metal must be poured soon after grain refinement treatment, or the titanium will no longer be available to act as a grain refiner.

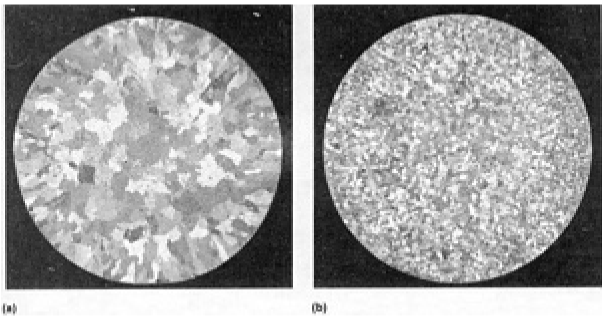


Fig. 3 As-cast Al-7Si ingots showing the effects of grain refinement. (a) No grain refiner. (b) Grain refined. Both etched using Poulton's etch; both 2×

Refinement of Hypoeutectic Alloys. Many sand and permanent mold aluminum-silicon alloys are hypoeutectic and benefit from refinement or "modification" of the silicon eutectic phase. This is done by adding small amounts of sodium, strontium, calcium, or antimony to the melt prior to pouring. These elements reduce the size of the eutectic silicon plates that form, decrease their interlamellar spacing, and change their morphology (Fig. 4). This change in silicon morphology improves casting properties. Silicon, strontium, and calcium are compatible, meaning that they can be mixed, an important consideration when charges may be made up from purchased scrap. Antimony, however, is not compatible with the other modifiers, and must be kept out of melts containing them.

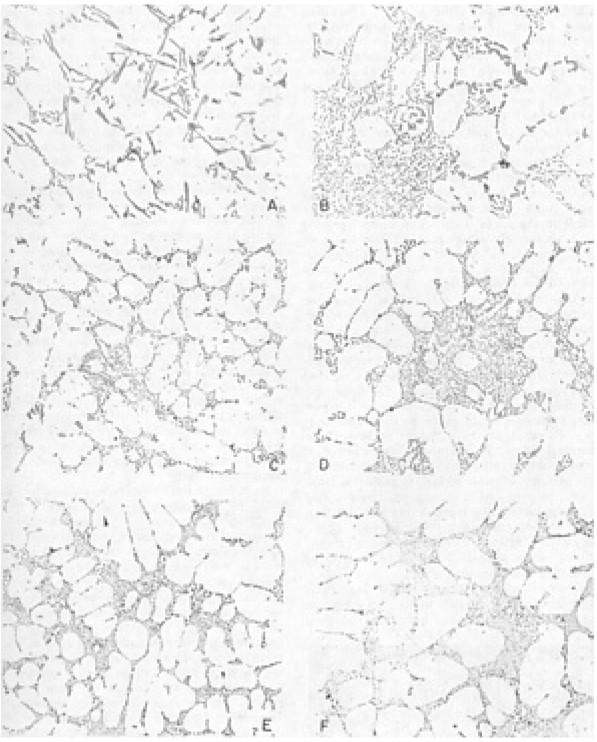


Fig. 4 Varying degrees of aluminum-silicon eutectic modification ranging from unmodified (A) to well modified

(F)

The use of strontium and sodium is usually accompanied by an increase in hydrogen content of the melt. Inert gas degassing treatments must be used in this case. Because the silicon eutectic can also be modified by rapid cooling rates, foundries that pour thin-section castings (that solidify rapidly) often do not add modifiers to their melts. When using modifiers, the phosphorus content of the melt must be kept below 5 ppm in hypoeutectic alloys.

Refinement of Hypereutectic Alloys. In hypereutectic aluminum-silicon alloys, phosphorous, in the form of phosphor-copper or phosphorous pentachloride, changes the distribution and morphology of the silicon phase (Fig. 5). In refining hypereutectic melts, the bath temperature should be kept to a minimum, and impurities that react with phosphorous should be removed prior to modification treatment. Phosphorus refinement substantially improves mechanical properties and castability of hypereutectic alloys.

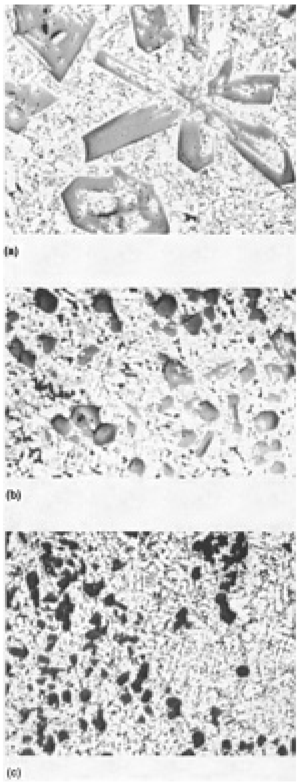


Fig. 5 Effect of phosphorus refinement on the microstructure of Al-22Si-1Ni-1Cu alloy. (a) Unrefined. (b) Phosphorus-refined. (c) Refined and fluxed. All 100×

Sand Casting and Permanent Mold Alloys

Alloy Compositions. Although a great many aluminum casting alloys have been developed, only a few are used widely. These are the hypoeutectic aluminum-silicon alloys containing small amounts of magnesium and/or copper. Table 1 lists compositions of common aluminum-silicon alloys. Copper is also used in some alloys as the major alloying constituent. The most popular alloy, A356.0, used for most automotive and general purpose castings, contains 6.5 to 7.5% Si and 0.25 to 0.45% Mg. A variation of this alloy, used for aircraft castings, increases the magnesium content to 0.55 to 0.60% while reducing the level of residual elements allowed in the alloy.

Table 1 Compositions of common aluminum-silicon alloys

Alloy	Product(a)	Nominal composition(b), %				
		Cu	**Mg**	**Mn**	**Si**	**Others**
355.0	S, P	1.2	0.50	0.50 max	5.0	0.15Ti
A356.0	S, P	. . .	0.35	0.35 max	7.0	. . .
A357.0	S, P	. . .	0.60	0.03 max	7.0	0.15Ti, 0.04Be
360.0	D	. . .	0.50	0.35 max	9.5	. . .
380.0	D	3.5	. . .	0.50 max	8.5	. . .
390.0	D	4.5	0.60	0.10 max	17.0	. . .
413.0	D	. . .	. . .	0.35 max	12.0	. . .
B443.0	S, P	. . .	. . .	0.50 max	5.2	. . .

(a) S, sand casting; P, permanent mold casting; D, die casting.

(b) All compositions contain balance of aluminum.

Eliminating Microporosity. A major problem in the manufacture of aluminum alloy castings is elimination of microporosity. These alloys have large mushy zones (liquidus-to-solidus spreads) and, because of the high heat of fusion of aluminum, tend to solidify more slowly than iron castings. Delivery of feed metal to areas where shrinkage is occurring in the casting is difficult, as the feed metal must wind its way through the growing dendrites. When the mesh of dendrites becomes coherent, which occurs when the casting is less than 50% solid, movement of liquid metal through the dendrite mesh becomes extremely difficult and microporosity results. Pore size is increased by the presence of hydrogen gas coming out of solution, which is why it is important to thoroughly degas the metal before pouring. However, as the shrinkage pores nucleate heterogeneously on inclusions, the number of pores can be significantly reduced by eliminating the presence of oxide inclusions and oxide films in the casting. This is accomplished by avoiding the introduction of oxygen during melting, carefully removing the oxide skin that forms spontaneously on the surface of the melt, using ceramic filters in the mold, and filling the mold using counter-gravity techniques.

The most effective way to eliminate porosity in aluminum alloy castings is to decrease the length of the mushy zone through which the feed metal must travel during solidification. This is done by establishing very high thermal gradients in the casting by arranging metal chills and risers in the mold strategically and insulating the risers. Castings made using this practice are often referred to as "premium quality castings." Alloys commonly considered premium by definition and specifications are 201.0, C355.0, A206.0, A356.0, 224.0, A357.0, 249.0, 358.0, and 354.0. Unfortunately, the high heat of fusion of these alloys limits the section size over which it is possible to establish effective thermal gradients. For this reason, few aluminum castings are made in sections heavier than 25 mm (1 in.). Complete elimination of microporosity in aluminum castings is generally not possible, unless the castings are hot isostatically pressed after casting. It should be pointed out that the techniques used to control microporosity generally reduce it to a level where it has little effect on static and dynamic properties.

Melt Practice. Degassing, addition of grain refiner and addition of the eutectic modifier are carried out during melting. Avoiding oxide formation is a major concern in melting and pouring. Molten metal transfer from melting furnace to pouring ladle must be done with minimum turbulence. When gravity pouring is used to fill the mold, it is essential to position the pouring ladle as close to the pour cup as possible, in no case more than 25 mm (1 inch) above the cup. Turbulence must be avoided in the flowing stream. As in the casting of ferrous metals, venting the mold is important to assure that the mold fills evenly.

Permanent molding is often used to make aluminum alloy castings. In this case the thermal gradients may be established by using the metal mold as the chill and placing resin-bonded sand inserts in the mold to slow solidification in that area. Permanent molding is widely used in the automobile industry.

Heat Treatment. Aluminum casting alloys develop their properties as a result of heat treatment. The heat treatments used are generally solution heat treatment, quenching, and aging. The aging treatment employed can be varied to control specific properties to a desired specification. In solution heat treatment, the casting is heated into the single-phase zone on the phase diagram but generally not above the eutectic temperature (Fig. 6). To obtain the maximum advantage from solutionizing treatments, there must be as little segregation in the cast structure as possible, as heavily segregated castings contain pockets of segregated alloying elements that melt at temperatures below the solutionizing temperature. These areas melt during heat treatment but do not re-solidify with the proper structure, thereby substantially decreasing casting properties. Segregation is avoided by using rapid solidification rates and restricting the amount of low-melting point elements in the alloy composition. As most permanent mold and sand castings are solidified at as high a rate as can be obtained to minimize the formation of microporosity, segregation is rarely a problem.

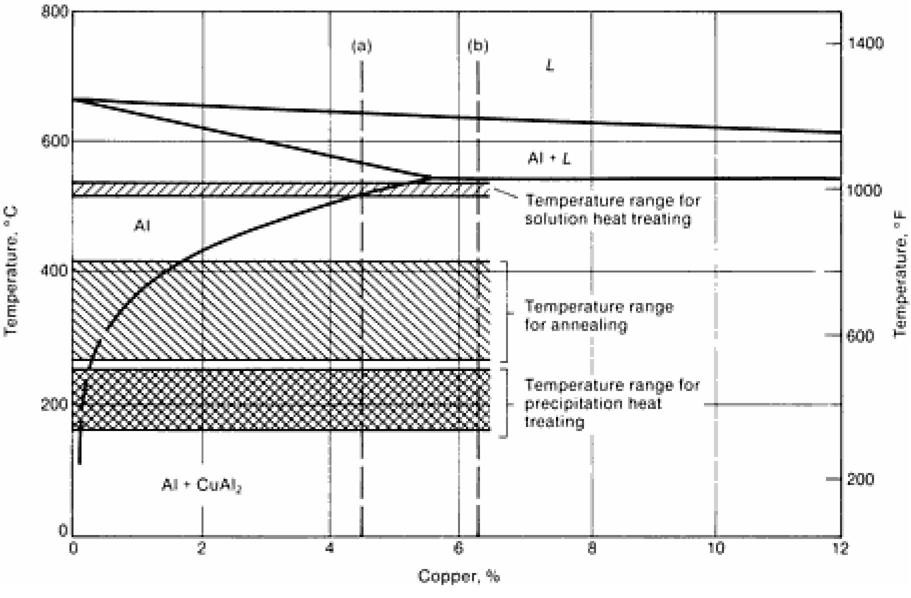


Fig. 6 Portion of aluminum-copper binary phase diagram. Temperature ranges for annealing, precipitation heat treating, and solution heat treating are indicated.

Castings are held at the solutionizing temperature long enough to dissolve the alloying elements into the matrix. The amount of time required varies with the alloy, section size, and solutionizing temperature; higher temperatures require less time. The time also varies with section thickness; thicker sections take longer to reach the solutionizing temperature. No special atmosphere controls are needed for aluminum heat treatment. However, control of the furnace temperature in all parts of the furnace is essential to avoid overheating and the possibility of melting interdendritic regions where some microsegregation exists.

After solution heat treatment, the castings are quenched to retain the alloying element in supersaturated solution. The quenchant used is normally water held near its boiling point. Although better properties are obtained when castings are quenched into room temperature or refrigerated water, quenching often distorts castings, and the degree of distortion increases as the quenchant temperature decreases. Distortion occurs because different parts of the casting cool at different rates, depending on their surface area-to-volume ratio (as in solidification) and, more importantly, on whether or not bubbles of steam form on the surface in the quenching medium, thereby insulating that section of the casting and slowing its cooling rate. Distortion results from the stresses set up as the casting contracts during cooling and when sections of the casting cool at rates different from that of neighboring sections, thus contracting at different rates. The key to minimizing quench distortion is to obtain uniform cooling over all parts of the casting. One quenching method that does this is quenching into a fluidized bed of small refractory particles.

After the castings are quenched, they are heated to an intermediate temperature to precipitate the supersaturated phases that strengthen the casting and give it its properties. The properties developed depend on the alloy, the temperature selected, and the time the casting is held at the aging temperature. Castings are air cooled after aging. Aluminum castings may be annealed to remove residual stresses; however, annealing destroys the effects of the aging treatment.

Die Casting Alloys

Alloy Compositions. Alloys used in sand casting are rarely used in pressure die casting. This is because the steel die material is soluble in molten aluminum. Therefore, iron is added to die casting alloys in amounts above 0.7%, which stops dissolution of the die in the alloy. Low-iron alloys solder to the die, and the castings cannot be removed from the die easily. (The problem is avoided in permanent mold castings by applying a refractory coating to the surface of the mold.) The most commonly used die casting alloys contain 7.5 to 9.5% Si, 1.3 to 2% Fe, 3 to 4% Cu, and 0.5% Mn. Of these, Alloy 380 listed in Table 1 and its variations predominate. Magnesium is not added to die casting alloys because it oxidizes during the shot and forms inclusions in the casting.

The addition of iron, unfortunately, lowers casting ductility. In addition, iron reacts with other alloying elements to form insoluble intermetallic compounds in the melt. These intermetallics have the beneficial effect of increasing alloy strength, particularly at higher temperatures. However, these insoluble compounds can build up in melting and holding furnaces and transfer launders, creating a sludge that, if inadvertently included in the metal used for a casting, produces hard and brittle inclusions in the casting. Die casters are familiar with composition limits that prevent sludge formation. A common rule is that iron content plus two times manganese content plus three times chromium content should not exceed the sum of 1.7%. This limit is arbitrary and inexact; it is often assigned values from 1.5 through 1.9%, and it is subject to the specific composition and actual minimum process temperature.

Melt practice for die casting alloys differs from that for sand and permanent mold alloys, primarily because the high velocities under which the metal enters the die in this casting process often trap air in the casting. Because of this, properties of die castings are not expected to be as high as those of sand and permanent mold castings. Therefore degassing, grain refinement, and eutectic modification are traditionally not done in preparing die casting melts. However, the development of vertical squeeze casting and slow-fill techniques that eliminate the entrapment of air into the casting are now permitting die casters to make use of melt preparation methods that eliminate gas and inclusions and lead to much higher properties in die castings than those obtainable before. The vertical squeeze casting process is described and illustrated in the article "Molding Methods" in this Section (Fig. 22).

Heat Treatment. Because of the entrapped air in conventional die castings, these alloys are not heat treated (the air expands during heating, forming blisters on the surface of the casting). However, as castings made by the vertical squeeze casting method are generally free of entrapped air, they may be heat treated to develop a variety of useful properties.

Copper Alloys

COPPER is alloyed with other elements because pure copper is extremely difficult to cast and prone to surface cracking, porosity problems, and the formation of internal cavities. The casting characteristics of copper can be improved by the addition of small amounts of elements including beryllium, silicon, nickel, tin, zinc, chromium, and silver. When casting copper alloys, the lowest possible pouring temperature needed to suit the size and form of the solid metal should be adopted to encourage as small a grain size as possible as well as to create a minimum of turbulence of the metal during pouring. Recommended pouring temperatures for copper foundry alloys are listed in Table 2.

Table 2 Pouring temperatures of copper alloys

Alloy type	UNS No.	Light castings		Heavy castings	
		°C	**°F**	**°C**	**°F**
Group I alloys					
Copper	C81100	1230-1290	2250-2350	1150-1230	2100-2250
Chromium copper	C81500	1230-1260	2250-2300	1205-1230	2200-2250
Yellow brass	C85200	1095-1150	2000-2100	1010-1095	1850-2000
	C85400	1065-1150	1950-2100	1010-1065	1850-1950
	C85800	1150-1175	1950-2150	1010-1095	1850-2000
	C87900	1150-1175	1950-2150	1010-1095	1850-2000
Manganese bronze	C86200	1150-1175	1950-2150	980-1065	1800-1950
	C86300	1150-1175	1950-2150	980-1065	1800-1950
	C86400	1040-1120	1900-2050	950-1040	1750-1900
	C86500	1040-1120	1900-2050	950-1040	1750-1900
	C86700	1040-1095	1900-2000	950-1040	1750-1900
	C86800	1050-1175	1950-2150	980-1065	1800-1950
Aluminum bronze	C95200	1120-1205	2050-2200	1095-1150	2000-2100
	C95300	1120-1205	2050-2200	1095-1150	2000-2100
	C95400	1150-1230	2100-2250	1095-1175	2000-2150
	C95410	1150-1230	2100-2250	1095-1175	2000-2150
	C95500	1230-1290	2250-2350	1175-1230	2150-2250

	C95600	1120-1205	2050-2200	1095-1205	2000-2200
	C95700	1065-1150	1950-2100	1010-1205	1850-2200
	C95800	1230-1290	2250-2350	1175-1230	2150-2250
Nickel bronze	C97300	1205-1225	2200-2240	1095-1205	2000-2200
	C97600	1260-1425	2300-2600	1205-1315	2250-2400
	C97800	1315-1425	2400-2600	1260-1315	2300-2400
White brass	C99700	1040-1095	1900-2000	980-1040	1800-1900
	C99750	1040-1095	1900-2000	980-1040	1800-1900
Group II alloys					
Beryllium copper	C81400	1175-1220	2150-2225	1220-1260	2225-2300
	C82000	1175-1230	2150-2250	1120-1175	2050-2150
	C82400	1080-1120	1975-2050	1040-1080	1900-1975
	C82500	1065-1120	1950-2050	1010-1065	1850-1950
	C82600	1050-1095	1925-2000	1010-1050	1850-1925
	C82800	995-1025	1825-1875	1025-1050	1875-1925
Silicon brass	C87500	1040-1095	1900-2000	980-1040	1800-1900
	C87800	1040-1095	1900-2000	980-1040	1800-1900
Silicon bronze	C87300	1095-1175	2000-2150	1010-1095	1850-2000
	C87600	1095-1175	2000-2150	1010-1095	1850-2000
	C87610	1095-1175	2000-2150	1010-1095	1850-2000
Copper nickel	C96200	1315-1370	2400-2500	1230-1315	2250-2400

	C96400	1370-1480	2500-2700	1290-1370	2350-2500
Group III alloys					
Leaded red brass	C83450	1175-1290	2150-2350	1095-1175	2000-2150
	C83600	1150-1290	2100-2350	1065-1175	1950-2150
	C83800	1150-1260	2100-2300	1065-1175	1950-2150
Leaded semired brass	C84400	1150-1260	2100-2300	1065-1175	1950-2150
	C84800	1150-1260	2100-2300	1065-1175	1950-2150
Tin bronze	C90300	1150-1260	2100-2300	1040-1150	1900-2100
	C90500	1150-1260	2100-2300	1040-1150	1900-2100
	C90700	1040-1095	1900-2000	980-1040	1800-1900
	C91100	1040-1095	1900-2000	980-1040	1800-1900
	C91300	1040-1095	1900-2000	980-1040	1800-1900
Leaded tin bronze	C92200	1150-1260	2100-2300	1040-1175	1900-2150
	C92300	1150-1260	2100-2300	1040-1150	1900-2100
	C92600	1150-1260	2100-2300	1050-1150	1920-2100
	C92700	1175-1260	2150-2300	1065-1175	1950-2150
High-leaded tin bronze	C92900	1095-1205	2000-2200	1040-1095	1900-2000
	C93200	1095-1230	2000-2250	1040-1121	1900-2050
	C93400	1095-1230	2000-2250	1010-1150	1850-2100
	C93500	1095-1205	2000-2200	1040-1150	1900-2100
	C93700	1095-1230	2000-2250	1010-1150	1850-2100

	C93800	1095-1230	2000-2250	1040-1150	1900-2100
	C94300	1095-1205	2000-2200	1010-1095	1850-2000

Types of Copper Alloys

Copper alloys (brass and bronze) for the foundry industry are grouped into three classifications, depending on the spread between their liquidus and solidus temperatures (i.e., their freezing range or the size of the mushy zone during solidification). As the mushy zone increases, so does the difficulty of making sound castings. Table 2 categorizes the three groups of copper casting alloys. Compositions and properties of these alloys can be found in the Section "Copper and Copper Alloys" in this Handbook.

Group I alloys have a narrow freezing range, that is, a range of 50 °C (90 °F) between the liquidus and solidus.

Group II alloys are those that have an intermediate freezing range, that is, a freezing range of 50 to 110 °C (90 to 200 °F) between the liquidus and the solidus.

Group III alloys have a wide freezing range of well over 110 °C (200 °F), even up to 170 °C (300 °F).

Melting and Casting Practice

Copper-base alloys are melted in oil- and gas-fired crucible and open flame furnaces as well as electric induction furnaces. Both core type and coreless induction melters are widely used. Copper alloys are poured into many types of molds such as green sand, shell, investment, plaster, permanent mold (mold washes are employed), resin-bonded sand, centrifugal, and die. Melting and casting practice varies depending on the alloy group.

In the Group I alloys, pure copper and chromium copper are particularly prone to picking up hydrogen gas during melting and are normally melted under a flux to avoid oxidation and gas pickup. Alloys containing substantial amounts of zinc are subject to "flaring," the volatilizing of zinc from the melt. The zinc vapor instantly reacts with oxygen in the atmosphere, forming zinc oxide, a white powder that is easily visible to the melter. Aluminum additions help control flaring. These alloys do not require fluxing, and zinc additions are often added just before pouring to compensate for losses due to flaring. Aluminum bronzes and nickel bronzes dissolve gas easily and therefore must be melted under a flux in an oxidizing atmosphere (i.e., if a fuel-fired furnace is used for melting, the flame must be controlled so that the furnace atmosphere is oxidizing, not reducing). No fluxes are needed for white brasses.

In the Group II alloys, beryllium coppers require no fluxes. However, beryllium is toxic, so care must be exercised to capture all fumes from the furnace. Silicon brasses and bronzes do not normally require a flux and do not pick up gas unless superheated to excessively high temperatures. Copper-nickel alloys are susceptible to hydrogen pickup and therefore are melted as quickly as possible, deoxidized, and poured; fluxing is not necessary if the charge is cleaned before melting.

Group III alloys should be deoxidized before pouring. Because of the large mushy zone (large freezing range), it has been found that chilling or the establishment of a steep thermal gradient in the mold is necessary to produce sound castings. With these alloys, cover fluxes are seldom used.

Leaded red and yellow brasses were used widely for plumbing components. Lead is added to these alloys to assure pressure tightness. However, concern over the toxicity of lead has resulted in regulations which forbid its presence in municipal water supplies. In addition, disposal of sand from foundries pouring lead-containing alloys is strictly regulated (lead vaporizes during pouring and condenses on the sand grains). For this reason a new series of plumbing alloys known as SeBiloys have been developed. These alloys contain selenium in the range of 0.25 to 1.2% and bismuth in the range of 0.5 to 2.5% in place of lead. These alloys have both casting and mechanical properties similar to the alloys they replace.

Zinc Alloys

DIE CASTING is the process most often used for shaping zinc alloys although gravity casting (sand and permanent mold) is also employed. Some zinc castings have also been produced by the semisolid casting process.

Types of Zinc Alloys

Zinc foundry alloys are classified as either hypoeutectic or hypereutectic. The hypoeutectic alloys contain less aluminum (close to 4% Al) and 0.25 to 1.25% Cu. These alloys are die cast. Included in this group are Alloy No. 3, Alloy No. 5, and Alloy No. 7. The hypereutectic alloys have higher aluminum contents (5.0% up to 28% Al), copper contents up to 2%, and can be die cast, sand cast, or cast in permanent molds. Included in this group are ZA-8, ZA-12, and ZA-27. Compositions and properties of these alloys are given in the article "Zinc and Zinc Alloys" in this Handbook.

Melting and Casting Practice

Melting. Most melting is carried out using cast iron crucibles in fuel-fired furnaces. Gas-fired immersion tube furnaces (in which the gases burn in metal tubes that are inserted in the bath) are also popular. Fluxing is not needed when clean ingot is used but may be required when foundry returns are used. Because zinc oxidizes easily, any activity that mixes oxygen into the melt, such as excessive stirring or turbulent metal transfer, should be avoided. Excessive melting and holding temperatures will oxidize the melt and lead to zinc flaring and will require adjustment of melt chemistry before pouring. Lead, cadmium, and tin levels must be held below 0.004% (or less in some alloys) to prevent die cast parts from swelling or cracking in service.

Die Casting. Zinc alloys are most commonly die cast using hot chamber machines, although cold chamber machines are used for casting some hypereutectic alloys (ZA-12 and ZA-27). These die casting machines are easily automated and have high production rates. Because zinc has a low melting temperature, hot-work tools steels are not necessary for die materials though recommended for high volume parts. The optimum die temperature for zinc die castings is generally between 160 and 245 °C (325 to 475 °F), although higher temperatures are recommended when a hardware finish is specified for the part. Die temperature should be controlled to within 5 °C (9 °F).

Sand Casting. The ZA alloys, especially ZA-12 and ZA-27, are being used increasingly in gravity sand casting operations. The wide freezing range of the ZA-27 alloy (~109 °C, or 200 °F) means that control of solidification is especially important for this alloy. The use of chills or patterns that promote directional solidification is recommended.

Permanent mold casting is done using both metallic and machined graphite molds. Cast iron or steel is commonly used for metallic permanent molds. The use of graphite molds permits as-cast tolerances similar to those obtained in die casting.

Magnesium Alloys

MAGNESIUM ALLOY CASTINGS can be produced by nearly all of the conventional casting methods, namely, sand, permanent and semipermanent mold, shell, investment, and die casting. The choice of a casting process for a particular part depends on factors such as configuration of the proposed design, the application, properties required, and the total number of castings required. However, because magnesium reacts violently with moisture and with the oxygen in the air, a number of precautions must be taken when melting, pouring, and heat treating magnesium alloy castings.

Types of Foundry Alloys

Foundry alloys vary with the type of molding method used. Three systems of magnesium alloys are used for high-pressure die casting: magnesium-aluminum-zinc-manganese (AZ), magnesium-aluminum-manganese (AM), and magnesium-aluminum-silicon-manganese (AS). Systems used for sand and permanent mold castings include: magnesium-aluminum-manganese with and without zinc (AM and AZ), magnesium-zirconium (K), magnesium-zinc-zirconium with and without rare earths (ZK, ZE, and EZ), magnesium-thorium-zirconium with and without zinc (HK, HZ, and ZH), magnesium-silver-zirconium with rare earths or thorium (QE and QH), magnesium-yttrium-rare earth-zirconium (WE), and magnesium-zinc-copper-manganese (ZC). Compositions and properties of these alloys are listed in the Section "Magnesium and Magnesium Alloys" in this Handbook.

The AZ family of alloys is grain refined by the addition of pellets of hexachlorethane to the melt before pouring. The zirconium content of Mg-Zr alloys acts as its own grain refiner.

Melting and Casting Practice

Melting. Magnesium is usually melted in a steel crucible in a fuel-fired or electric resistance furnace. Because molten magnesium burns in air, it is essential to exclude air and oxygen from the surface of the melt. If a flux is used, a small quantity of flux (about 1.5% of the total charge weight) is placed in the crucible before it is charged, and the crucible is preheated to a dull red heat. The charge, which must be thoroughly cleaned to prevent sand or oxide phases from entering the melt (where they would react with the metal) and preheated to drive off all moisture, is then progressively fed into the crucible. The object is to maintain a steadily advancing level of liquid alloy in the crucible, with no splashing as charge ingots are added. More flux is sprinkled on the surface of the melt during this process, whenever bare metal is seen by the melter. The fluxes are proprietary mixes developed for use with specific alloys. The flux must be removed from the melt surface prior to pouring, and a sulfur/boric acid powder is sprinkled on the surface of the stream during pouring to prevent formation of magnesium oxide, which, if uncontrolled, will result in a magnesium fire.

In the fluxless technique, widely used in die casting, an air/sulfur hexafluoride or air/carbon dioxide/sulfur hexafluoride ($\leq$2% SF_6) is fed to the surface of the melt and protects the molten surface during pouring. In sand casting practice, the amount of SF_6 is generally increased, and the carrier gas may be entirely carbon dioxide.

Sand Casting. Successful production of sand castings became possible only when the means for preventing metal/mold reactions were developed. This was achieved by the additions of suitable inhibitors to the sand mix used in the manufacture of the mold and the cores. These inhibitors include boric acid, sulfur, potassium fluoborate, and ammonium fluosilicate, and they are added in an amount equal to that of the moisture content of the sand. Diethylene glycol is often added to the sand mix to decrease the amount of moisture needed in the sand mix. Because large quantities of gas are generated during pouring, the sand must have high permeability, which implies the use of a fairly coarse sand grain size and extensive venting of the casting and the gating systems. Inhibitors must be added to core mixes to prevent reaction with the cores. The amount of inhibitor to add to the sand mix increases as the size of the casting increases and its cooling rate decreases, because inhibitors often volatilize during cooling of the casting. It is absolutely essential to add sufficient inhibitor to sand molds and cores to prevent mold explosions that can occur at any time until the casting is solid if the inhibitor content is too low.

Die casting is a particularly attractive process for magnesium. Because it has a lower heat of fusion than aluminum, casting cycles can be up to four times faster, and die wear is significantly reduced. Molten metal systems can be isolated from the atmosphere in fluxless melting. Because molten magnesium does not attack iron and steel, hot chamber machines may be used. Dies are operated in the temperature range of 260 °C ± 14 °C (500 °F ± 25 °F).

Gating and Risering Practice. An unpressurized gating system is used, and it is important that the metal enter the casting cavity from the bottom and fill the cavity progressively. Waterfalling (the dropping of metal from one level in the mold to a lower level during mold filling) must be avoided. Turbulence must also be minimized during pouring. Screens and filters are usually placed in the gating system to trap inclusions. Risers are often insulated to increase their feeding efficiency.

Castings are finished using standard techniques. Refractory media, not steel shot, is used in blast cleaning the castings. A protective atmosphere must be used during heat treating.

Superalloys

SUPERALLOYS are primarily nickel-base alloys containing substantial quantities of chromium, cobalt, refractory elements such as molybdenum and tungsten, and up to 7% Ti plus Al. Superalloys are inherently non-machinable and, as many are too brittle to forge, must be cast. They have a wide liquidus-to-solidus spread and are difficult to feed. They are primarily produced by investment casting and are most widely used in the gas turbine engine industry. The complex metallurgy of the superalloys as well as their compositions and properties are described in the article "Superalloys" in this Handbook.

Melting and Casting Practice

Vacuum Melting. Because of the high aluminum and titanium contents of the melt and the stringent requirements for casting cleanliness, these alloys are vacuum induction melted from prealloyed charges. Magnesia crucibles are most often used. Usually only enough metal is melted for one mold. Multiple-chamber vacuum furnaces are used. The melt chamber is kept at melt pressure of around 10^{-3} torr continuously. The charge is placed in a charge lock that is evacuated, and when the pressure in the charge lock is equal to that of the melting furnace, a mechanical device places the charge in the induction melting furnace. When the charge is melted, the mold is placed in the mold lock (generally located beneath the melting chamber) and the mold lock is evacuated. When the pressure in the mold lock reaches the pressure in the melting chamber, a valve between the chambers opens and the mold is raised into the melting chamber, where it is poured. The mold and solidifying metal are then retracted into the mold chamber, and the melting sequence can begin again, making maximum use of the facility.

Pouring. Because melting, pouring, and solidification take place in a vacuum, superalloys may be poured at very high pouring rates, around 50 kg/s (110 lb/s). These high pouring rates are frequently necessary to fill the thin sections often encountered in gas turbine hardware. Filling of thin sections is also made easier by preheating the molds to temperatures above 900 °C (1650 °F).

Directional Solidification. Because gas turbine blades are primarily stressed in one direction, it was realized that their performance could be improved if there were no grain boundaries perpendicular to the principal stress axis of the blade. This led to the development of the directional solidification process. In this process the investment mold is left open at its bottom, which is placed on a water-cooled copper plate prior to pouring. The mold is raised into the melt chamber that also contains a mold heater that is typically an induction-heated graphite susceptor. The mold is heated to a temperature above the melting point of the superalloy and filled with metal. The solid nucleates on the copper chill, and the grains begin to grow into the molten metal. Because the growth of nickel-base alloy grains during solidification is easiest in the [001] direction, those grains which have their [001] directions most nearly perpendicular to the chill plate will grow most easily. The mold is then withdrawn slowly from the heater (Fig. 7a). This removal causes the grains to grow from the bottom of the mold to the top of the mold and the resulting casting structure to consist of parallel grains running the length of the casting.

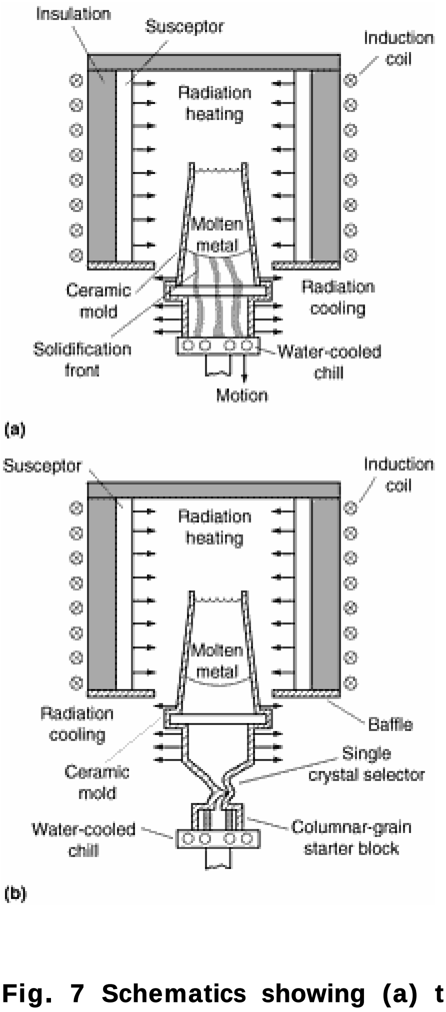

Insulation
Susceptor
Induction coil
Radiation heating
Molten metal
Ceramic mold
Radiation cooling
Solidification front
Water-cooled chill
Motion
(a)
Susceptor
Induction coil
Radiation heating
Molten metal
Radiation cooling
Baffle
Single crystal selector
Ceramic mold
Water-cooled chill
Columnar-grain starter block
(b)

Fig. 7 Schematics showing (a) the directional solidification process and (b) the single-crystal solidification

process for casting of superalloys

Single Crystal Casting. After the development of directional solidification, it was realized that the elevated temperature capability of superalloys could be increased if grain boundaries, which melt at lower temperatures than the grains themselves, could be eliminated so that the resulting casting would be a single grain or a single crystal. This can be accomplished using the directional solidification process, arranging the solidification so that only a single grain is allowed to grow throughout the mold. Grain selection is accomplished either by seeding the mold (placing a solid seed at the bottom of the mold prior to pouring), or by the use of grain selectors (Fig. 7b). In the grain selector section of the mold, which is nearest the chill, the mold is arranged so that only the grain that is most favorably oriented with respect to the chill is able to grow from the chill plate into the casting cavity. The selector can be either a helix or a series of right angle segments. Grain selectors are easier for the foundry to use than seeds; the use of seeds is generally restricted to castings where the desired grain orientation is different from that of the direction of easy growth.

Titanium Alloys

TITANIUM AND ITS ALLOYS are attractive because they have the strength of steel but weigh only 60% as much as steel. However, the high reactivity of titanium, especially in the molten state, presents a special challenge to the foundry. For example, titanium reacts violently with silica and has a fairly high solubility for most other refractories (including oxides, carbides, and nitrides). As a result, titanium alloys cannot be melted in refractory crucibles, and they dissolve or react with all refractory molds.

Foundry Alloys

All production titanium castings to date are based on traditional wrought product compositions. As is the case with wrought alloys, Ti-6Al-4V is also the most popular casting alloy. More detailed information on titanium castings can be found in the Section "Titanium and Titanium Alloys" in this Handbook.

Melting and Casting Practice

Melting. Foundries generally use vacuum arc remelting (skull melting) or a vacuum induction melting technique in which a magnetic field is arranged to partially levitate the melt and keep it from touching the sides of the metal crucible.

Rammed Graphite Molding. Large heavy-section titanium castings can be made in rammed graphite molds. These molds are made using finely divided graphite as the molding aggregate, bound by a mixture of pitch, syrup, and starch. The molding material is rammed around the pattern in the same manner used in conventional green sand molding, and the mold is baked and fired to develop its strength.

Investment casting is used to produce most titanium aerospace and sporting equipment castings. Titanium investment casting differs from traditional ferrous investment casting only in the composition of the first two dipcoats and stuccos. Because silica reacts with molten titanium, the silica content of these first two coats must be minimized, and the refractory used in the dips and stuccos is selected from materials that are thermodynamically more stable than titanium dioxide. Investment cast molds may be preheated but are not normally preheated to temperatures as high as those used in nickel-base superalloys, to minimize the mold reaction.

In spite of these precautions, there will be a reaction between the molten metal and the mold that results in a layer of increased oxygen content on the surface of the casting. This layer, which varies in thickness up to as much as 1.5 mm (0.06 in.) depending on how long the casting took to solidify in the section, stabilizes the alpha phase of titanium and is known as the "alpha case." It is removed by chemical milling on those castings where its presence could lead to premature failure. Stock is deliberately added to patterns to compensate for the material that will be removed.

Because of the necessity of minimizing the amount of alpha case formed, titanium castings are usually solidified as rapidly as possible. This means that feeding is difficult and titanium castings often contain unacceptable amounts of porosity. For this reason, most titanium castings intended for high integrity applications are hot isostatically pressed as part of the standard finishing procedure.

Cast Metal-Matrix Composites

METAL-MATRIX COMPOSITES (MMCs) offer unique properties that may have advantages in certain applications. Both particulate-reinforced MMCs and fiber-reinforced MMCs can be produced by casting methods. Additional information on the processing and properties of MMCs can be found in the Section "Special-Purpose Materials" in this Handbook.

Casting MMCs

For particulate-reinforced composites, the reinforcing phase is dispersed in the melt by stirring, injection, or ultrasonic agitation. The reinforcing phase is generally non-wetting and usually differs in density from the matrix metal, which may cause the particles to float or sink in the melt. However, if the particles are in suspension, the resulting molten metal/particle slurry can be poured just as any casting alloy can be poured. Fluidity may be affected by the volume fraction of particles and the pouring temperature. Solidification rates are usually high enough that the particles are engulfed during solidification, not pushed ahead of the advancing solid interface. Typical uses for particulate MMCs are in automobile pistons (aluminum alloy/silicon carbide reinforcement) and in applications where high wear resistance is essential.

Fiber-reinforced composites are made by vacuum infiltration, pressure casting, or a combination of both. The object is to force the liquid into a mold cavity into which the fiber reinforcement has been preplaced. Care must be taken that the fibers do not freeze the molten alloy prematurely. It is common to treat the surface of the fibers to improve their wettability to the alloy being infiltrated. Aluminum, magnesium, copper, and superalloys have been used as matrix materials for these castings. Fiber reinforcements include boron, graphite, silicon carbide, and refractory metals.

Casting Design and Quality Assurance

Thomas S. Piwonka, The University of Alabama

Introduction

DESIGNING A COMPONENT as a casting requires special consideration be given to how the part will solidify. In addition to the general guidelines given in this article, design manuals are available from foundries and metalcasting trade and professional societies.

Design Considerations

Castings offer the designer cost advantages over other manufacturing methods for most components, especially those having complex geometries. Casting properties are usually isotropic, and castings may be designed for function rather than ease of assembly, like built-up structures. Fillet radii are usually generous, decreasing stress concentration factors. Converting a built-up assembly to a casting usually is accompanied by a decrease in part count, assembly time and inventory, and weight. With the development of rapid prototyping, expensive tooling is not necessary, and parts can be delivered within days after the order is placed.

Design and Properties. Designers face a number of challenges in the design of castings. Static property data often found in handbooks may consist of "typical values," which obscure a crucial fact: casting properties are determined during solidification and subsequent heat treatment. This determination means properties will vary depending on how quickly the casting solidifies and how the casting is heat treated.

Component design is usually approached with the assumption that the material is uniform and isotropic and that there is an inherent small and random scatter in properties. In castings, properties will be uniform in specific casting sections from casting to casting, provided the casting variables are constant for each casting. However, they may vary in a predictable manner from point to point within the casting.

Designers frequently use handbook data in designing components. Very often, this data is developed using the Gaussian statistics. As previously noted, such data can be misleading if it is not corrected to reflect differences in cooling rate from section to section within a casting. The Gaussian statistics are appropriate for those materials that are truly ductile (those that have a tensile elongation over 8 to 10%). Many casting alloys, however, even when discontinuity-free, have elongations of only 5 to 10%. Indeed, this is often the reason these alloys are commonly cast: their low ductilities make them hard to form by forging or machining. Use of the Gaussian statistics to determine design allowables in these alloys is incorrect and can lead to "casting factors" that cause significant overdesign, waste of material, and weight penalties. Casting factors are arbitrary increases in casting section thickness applied to compensate for perceived lack of reproducibility of casting properties.

Reproducibility of properties produced by a process is most important for the designer, as the components designed must behave according to the design. Reliability is often evaluated using the Weibull statistics. The Weibull statistics consider the probability of the existence of a discontinuity that would cause failure. This is particularly appropriate for the design of low ductility materials. In analyzing data using Weibull statistics, one evaluates the value of the Weibull modulus. The higher the Weibull modulus, the more reliable the material (i.e., the higher the Weibull modulus, the less the variation in property within a given section of the component).

General Design Rules. The most important principle of good casting design is that casting sections should freeze progressively, allowing the riser to supply liquid metal to feed shrinkage occurring during solidification. There are a number of excellent summaries of principles of good casting design (for example, the *Steel Castings Handbook,* jointly published by the Steel Founders' Society of America and ASM International) and a comprehensive booklet has been published on design of premium quality aluminum alloy castings (*Design and Procurement of High-Strength Structural Aluminum Castings,* published by the American Foundrymen's Society, Inc.). This publication also includes general information on the specification and process of approving foundry sources, which is applicable to castings made from any metal.

Designing for progressive solidification requires tapering walls so they freeze from one end to the other; (Fig. 1) and avoiding situations where two heavy sections are separated by a thin section (this is a poor design because metal must feed one heavy section through the thin section and, when the thin section freezes before the heavy section, the flow path will be cut off and shrinkage may form in the heavy section).

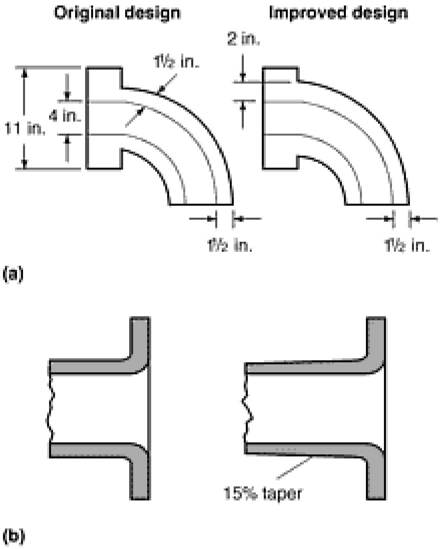


Fig. 1 Redesign of castings to provide progressive solidification through the use of tapered walls. (a) Elbow design. (b) Valve fitting design

Junctions also concentrate heat, leading to areas in the casting where heat is retained. These areas solidify more slowly than others, thus having a coarser structure and different properties from other sections, and solidify after the rest of the casting has solidified, so shrinkage cannot be fed. Minimizing the concentration of heat in junctions therefore aids in improving casting properties. Examples of this are shown in Fig. 2.

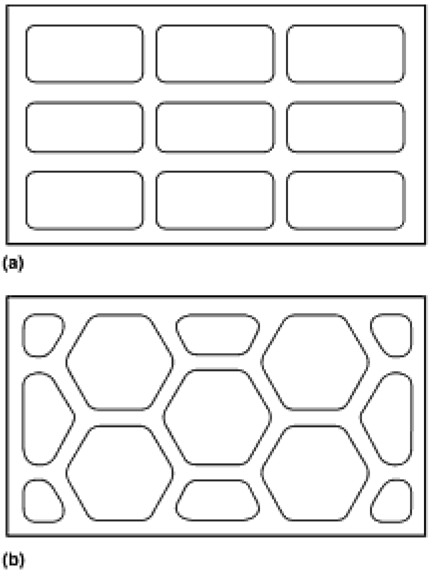


Fig. 2 Redesign of a casting to minimize heat concentration. (a) Design has numerous hot spots (X-junctions) that will cause the casting to distort. (b) Improved design using Y junctions

Concave corners concentrate heat, so they freeze later and more slowly than straight sections, while convex corners lose heat faster and freeze sooner and more quickly than straight sections. In designing a casting, the designer should use properties from test bars that have solidified at the actual cooling rate in that section of the casting. This cooling rate can be determined by instrumenting a casting and measuring the cooling rate in various sections or by simulating its solidification using a commercial solidification simulation program.

The hollow spaces in castings are formed by cores, refractory shapes placed in the molds and around which the casting freezes. These cores are later removed from the casting, usually by thermal or mechanical means. However, each core requires tooling to form and time for placement in the mold. Casting designs that minimize cores are preferable for minimizing costs. Some examples are given in Fig. 3.

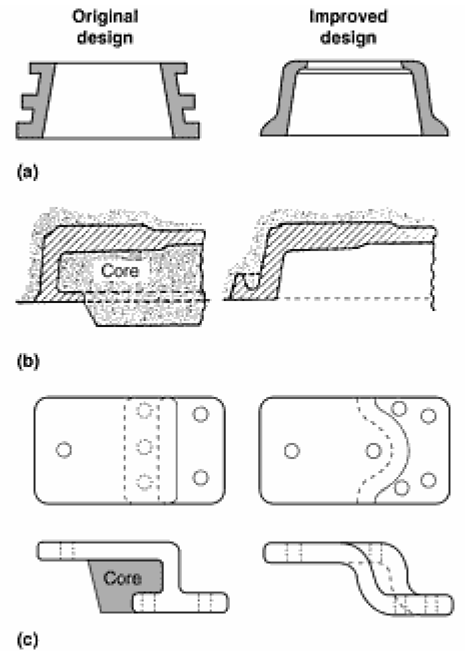


Fig. 3 Redesign of castings to eliminate cores. (a) Casting redesigned to eliminate outside cores. (b) Simplification of a base plate design to eliminate a core. (c) Redesign of a bracket to eliminate a core and to

decrease stress problems

The casting must solidify toward the riser in order to be sound, and gates must be located so the mold fills from the bottom to the top so that oxide films that form are swept to the top surface of the casting or into risers where they will not affect casting properties. Gate and riser locations must be accessible for easy removal to minimize processing costs. The position of gate and riser contacts also may add costs if placed where subsequent machining will be required to remove gate stubs or riser pads in the finished component.

Casting Design Summary. Casting design influences the way the castings solidify, and hence, the properties that are obtained. Many collections of casting data in handbooks overlook the effect of cooling rate on casting performance, and, as a result, do not provide adequate information for designers. Designers are therefore encouraged to work with foundries to develop databases of reliable mechanical property data that reflect the effect of cooling rates of the alloy and the sections the designer intends to use. This is particularly important for areas of the casting where stress concentrations are likely; use of a solidification simulation program (see following discussion) should assure that these areas are not also areas of slow solidification.

Designers should also be aware that different casting alloys have different levels of "castability," meaning that development of reliable casting properties may be more difficult in some alloys than others. Specification of a casting alloy solely on the results of test bar data (test bars are easy to cast and often do not reflect casting problems encountered in actual castings) without consulting the metalcaster can lead to high casting costs as the foundry compensates for castability difficulties with the alloy.

The designer must begin the design of a casting with an understanding of what properties are desired and required throughout the cast component. Flaw sizes must be kept below the critical level, and the designer should determine what that level is. Critical flaw sizes will vary according to location in the casting; that information should be reflected in specifications that also vary by location, in order to minimize manufacturing costs.

Casting Tolerances

Casting tolerances depend on the alloy being poured, the size of the casting, and the molding method used. Generally speaking, casting dimensional accuracy increases as one moves to the right in Fig. 4 and as the casting dimensions decrease. However, there is significant overlap between processes.

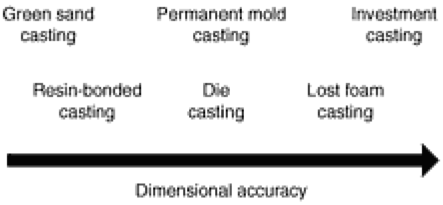


Fig. 4 General relationship between dimensional accuracy and casting process

Casting design also affects tolerances. Critical dimensions should not cross parting lines in molds or injection or core dies. Stresses that arise from unequal contraction of parts of the casting as it cools from solidification temperatures, as well as those that result from heat treating, can distort castings so they no longer conform to design dimensions. This also affects tolerances and may lead to extra costs to straighten castings. Solidification stresses are caused by shrinkage during casting solidification when different sections of the casting solidify at different times and rates. Because casting solidification rates depend on the casting design, the designer should consider the effect of the component design on casting distortion. Some examples are given in Fig. 5.

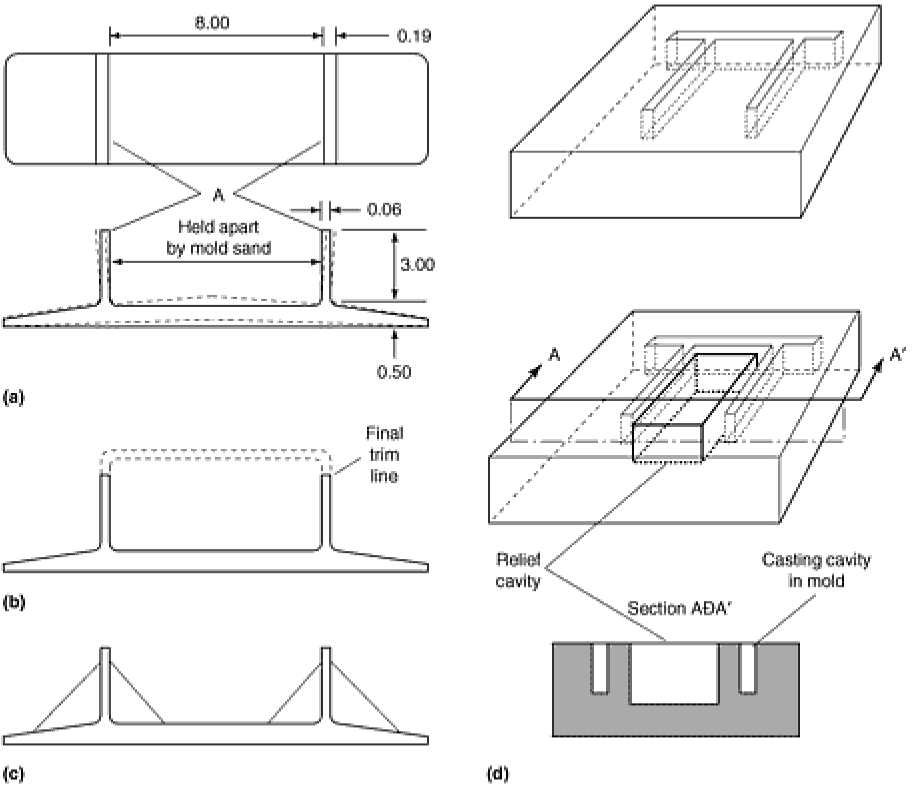


Fig. 5 Designing castings to prevent distortion caused by mold restraint. The original design, shown in top and front views in (a), was altered to three possible preventative designs, as follows. (b) Preferred method incorporating a tie bar. (c) Less effective method than that shown in (b). (d) Open cavity created in the molding media to relieve restraint upon flanges during casting solidification by allowing solid sand mass to collapse during shrinkage and minimize restraint. Dimensions given in inches

Solidification Simulation Programs

Since the cast structure controls the heat treated structure and the final structure controls the properties of the component, the designer must be able to predict the effect of the design on the structure of the final part. This is done today by using solidification simulation models. Most progressive foundries today use simulation models in engineering the casting process. Designers are encouraged to work with foundries and have them run solidification models on their designs in a concurrent design process to engineer castings that perform satisfactorily and are reasonably priced.

Solidification simulation models have been extensively developed over the last 20 years, and today there are a large variety to choose from. The more elementary models are based on Chvorinov's law and operate by comparing surface area to volume ratios of adjoining casting sections to predict the order in which the sections solidify (i.e., whether or not solidification will be progressive and shrinkage eliminated). Those models are satisfactory for predicting whether macroporosity will form on solidification; some models are effective at predicting the location of microporosity also.

Advanced models use finite element or finite difference methods to predict how the casting fills, and, from those results, establish the temperature of each point in the mold and each point in the liquid metal at the start of solidification. This produces a more accurate picture of the way the casting solidifies than is possible with models that consider only the surface area to volume ratio of adjacent casting sections. These models also are capable of predicting the grain size and structure and, from that information, are now being used to predict casting properties that result from a specific casting design and choice of casting process parameters. Some solidification models are capable of predicting distortion that will occur during casting and heat treatment and can be used to minimize residual stresses. Some commercial packages include expert systems to help orient the casting in the mold to minimize casting defects and to suggest gating and risering schemes.

Finite element and finite difference models represent the actual physical processes taking place during solidification. As such, they are inherently more accurate than models depending on statistics or heuristics (expert systems). However, statistical and expert system models can often serve as the starting point for a physics-base model. As the models are merely a tool for the foundryman to use in improving castings, no metalcaster should be intimidated by the physics or mathematics used to make up the model. Commercial models can be run by trained foundrymen with all educational backgrounds if they are interested in learning the instructions.

These models are a powerful tool for concurrent engineering of cast components. The designer, working with the foundry, can see the way the casting will solidify before the casting is poured. If problem areas are found with the design, it can be altered and the new design simulated. This iteration can be repeated until a satisfactory design is developed. When these simulations are combined with rapid prototyping methods, expedited delivery of cast components can be achieved.

Rapid Prototyping

Rapid prototyping (RP) is the use of a number of computer-aided design, layer-based processes to build temporary tooling for a manufacturing process. In casting, RP can be used to produce plastic or wax patterns for investment casting, actual investment casting molds, patterns for sand casting, and direct production of resin-bonded sand cores and molds. This means that a user of castings can obtain prototype quantities of parts from temporary tooling and that modifications can be made in the design before hard tooling is built.

All RP processes are based on the ability of a computer to slice a part into many parallel thin sections. The foundry's computer receives a data file of the geometry of the part from the customer and processes the solid model into sections. Based on these sections, the RP machine can then build up a pattern or a mold or core box by either fusing a pattern or mold material following directions from the computer or by cutting material that is glued together by a suitable adhesive to form the pattern or mold. The cutting or fusing is generally done using a laser guided by the computer program.

The materials used for prototype tools usually last for only a few parts. Tolerances of these prototype tools and patterns are generally acceptable for prototype evaluation, although not quite as good as hard tooling tolerances. However, they may be entirely acceptable for an application when only a few castings will ever be made. Time from part design to casting has been cut to as little as 48 h using RP processes, and the technique is especially valuable when bringing a new product or assembly to market. It should be noted that the most advanced of the RP devices combine solidification modeling programs with the RP process to automatically design gating and risering that will produce a satisfactory casting.

Quality Assurance in the Foundry

Consistent production of quality castings requires that the foundry exercise a high degree of control over a complex process. Casting dimensions are affected by the molding system, the pattern, the gating, the cores (aggregate, binder, coremaking method, and the way they are placed), and the pouring parameters. Freedom from inclusions in the casting depends on the melting, gating, and molding systems. Soundness and grain size control depend on gating and risering, casting design, melt practice, and melt treatment. Casting surface quality depends on mold and core materials and additives, mold surface coating, casting design, and pouring temperature.

Because of the large number of variables, foundries exercise continuous process control at a number of points in the casting process. Much of the information gathered is kept in the form of control charts that are analyzed using the tools of statistical process control. Control charts are routinely kept on molding variables (mold hardness, moisture content, sand temperature and compactability for green sand, slurry viscosity, temperature, plate weight for investment castings, etc.), metal composition (carbon equivalent, chill, and degree of nodularity for ductile iron and gas content and pouring temperature for aluminum alloys), and casting dimensions. These charts are used to plot trends in product attributes, giving the metalcaster warning when a process requires corrective action.

While traditional nondestructive testing methods (magnetic and fluorescent particle, radiographic, ultrasonic, and dimensional inspections) are routinely used either for 100% inspection or on a sampling basis, foundries prefer to apply statistical process control to the manufacturing process. As a result of the application of statistical process control and the acceptance by many foundries of the principals embodied in the ISO 9000 certification, metalcasting quality equals or exceeds that of other manufacturing processes.

Forming of Sheet, Strip, and Plate

Presses and Auxiliary Equipment for Forming Sheet Metal

THE PRESSES described in this article are mechanically or hydraulically powered machines used for producing parts from sheet metal. Power presses can be classified according to the following characteristics: source of power, type of frame, method of actuation of slides, and number of slides in action. Presses in any of these classes are available in a range of capacities (tonnage or bed area), although the range is not necessarily the same for all types of presses. Characteristics of 18 types of presses are summarized in Table 1.

Table 1 Characteristics of 18 types of presses

Type of press	Type of frame							Position of frame				Action			Method of actuation								Type of drive				Suspension			Ram		Bed		
	Open-back	**Gap**	**Straight-side**	**Arch**	**Pillar**	**Solid**	**Tie Rod**	**Vertical**	**Horizontal**	**Inclinable**	**Inclined**	**Single**	**Double**	**Triple**	**Crank**	**Front-to-back crank**	**Eccentric**	**Toggle**	**Screw**	**Cam**	**Rack and pinion**	**Piston**	**Over direct**	**Geared, overdrive**	**Under direct**	**Geared, underdrive**	**One-point**	**Two-point**	**Four-point**	**Single**	**Multiple**	**Solid**	**Open**	**Adjustable**
Bench	X	X				X		X		X	X	X			X		X		X		X	X	X				X			X		X	X	X
Open-back inclinable	X	X				X		X		X		X	X		X		X			X		X	X	X			X	X		X	X		X	
Gap-frame	X	X				X	X	X	X	X	X	X	X		X	X	X	X				X	X	X			X	X	X	X	X	X	X	
Adjustable-bed horn		X				X		X				X			X		X					X	X	X			X	X		X		X	X	X
End-wheel		X				X		X				X				X	X						X	X			X			X		X	X	
Arch-frame			X	X		X		X			X	X			X								X	X			X			X			X	
Straight			X	X		X	X	X	X		X	X	X	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	

-side																																
Reducing	X	X	X			X	X	X	X			X			X					X	X	X			X			X			X	
Knuckle-lever			X			X	X	X			X	X	X					X			X	X			X	X		X	X	X	X	
Toggle-draw			X			X	X	X					X	X	X		X	X				X		X	X	X	X		X		X	
Cam-drawing	X	X	X			X	X	X		X			X		X				X		X	X			X				X		X	
Two-point single-action		X	X			X	X	X			X	X			X		X					X		X		X		X		X	X	
High-production			X			X	X	X			X	X			X		X				X	X			X	X		X			X	
Dieing machine					X			X				X			X						X		X		X	X		X			X	
Transfer		X	X			X	X	X				X			X	X	X	X			X	X				X		X			X	
Flat-edge trimming				X		X		X					X						X			X			X			X				
Hydraul		X	X		X		X	X	X	X		X	X	X						X					X	X		X	X	X	X	X

ic												
Press brake	X	X	X	X	X	X	X	X	X	X	X	X

JIC Identification System

The Joint Industry Conference (JIC), a committee of press builders and large-press users formed some years ago, set guidelines for uniformity with respect to nomenclature, bed and ram sizes, force ranges, and symbols for presses (Fig. 1). Although the JIC is no longer in existence, most press builders adhere to the standards either completely or in part. Under the JIC press classification system with respect to the number of slides, the first letter in the designation is S for single-action, D for double-action, and T for triple-action presses. Most press builders place the JIC markings in a prominent position on the fronts of the presses.

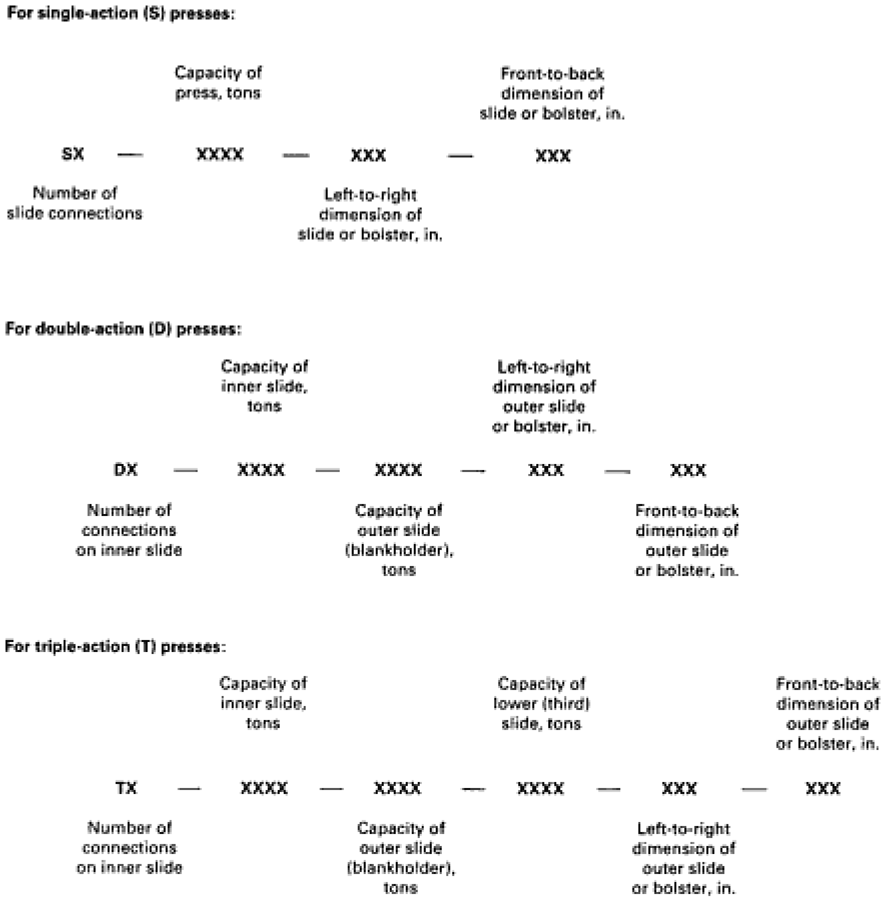

For single-action (S) presses:
Capacity of press, tons
Front-to-back dimension of slide or bolster, in.
SX — XXXX — XXX — XXX
Number of slide connections
Left-to-right dimension of slide or bolster, in.
For double-action (D) presses:
Capacity of inner slide, tons
Left-to-right dimension of outer slide or bolster, in.
DX — XXXX — XXXX — XXX — XXX
Number of connections on inner slide
Capacity of outer slide (blankholder), tons
Front-to-back dimension of outer slide or bolster, in.
For triple-action (T) presses:
Capacity of inner slide, tons
Capacity of lower (third) slide, tons
Front-to-back dimension of outer slide or bolster, in.
TX — XXXX — XXXX — XXXX — XXX — XXX
Number of connections on inner slide
Capacity of outer slide (blankholder), tons
Left-to-right dimension of outer slide or bolster, in.

Fig. 1 Designations used for press identification under the JIC classification system

Source of Power

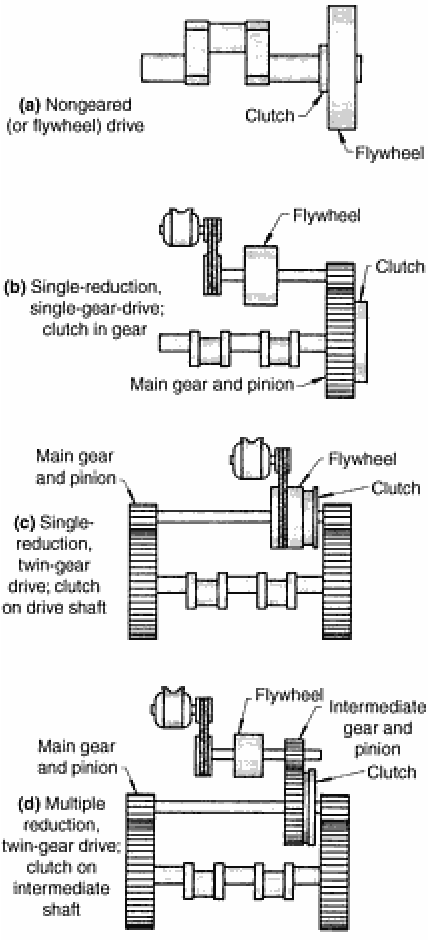
Power presses for sheet metal forming can be driven either hydraulically or mechanically. The performance characteristics and other operational features of hydraulic and mechanical presses are compared in Table 2.

Table 2 Comparison of characteristics of mechanical and hydraulic presses

Force	Capacity	Stroke length	Slide speed	Control	Preferred uses
Mechanical					
Varies depending on slide position	Practical maximum of ~54 MN (6000 tonf)	Limited	Higher than hydraulic, and can be varied. Highest at midstroke	Full stroke is usually required before reversal.	Preferred for operations requiring maximum pressure near the bottom of the stroke. Preferred for cutting operations such as blanking and piercing, and for relatively shallow forming and drawing (depths to about 102 mm, or 4 in.). Good for high-production applications and progressive and transfer die operations
Hydraulic					
Relatively constant (does not depend on slide position)	445 MN (50,000 tonf) or more	Capable of long (2.5 m, or 100 in.) strokes	Slower pressing speeds, with rapid advance and retraction. Speed is uniform throughout the stroke.	Adjustable; slide can be reversed at any position.	Good for operations requiring steady pressure throughout the stroke. Preferred for deep drawing, die tryout, flexible-die forming, drawing of irregular-shape parts, straightening, operations requiring high and variable forces, and operations requiring variable or partial strokes

Mechanical Presses. In most mechanical presses, a flywheel is the major source of energy applied to the slides by cranks, gears, eccentrics, or linkages during the working part of the stroke. The flywheel runs continuously, engaged by the clutch only when a press stroke is needed. In some very large mechanical presses, the drive motor is directly connected to the press shaft, thus eliminating the need for a flywheel and a clutch.

Two basic types of drives, gear and nongeared, are used to transfer the rotational force of the flywheel to the main shaft of the press (Fig. 2).



(a) Nongeared (or flywheel) drive
Clutch
Flywheel
Flywheel
Clutch
(b) Single-reduction, single-gear-drive; clutch in gear
Main gear and pinion
Main gear and pinion
Flywheel
Clutch
(c) Single-reduction, twin-gear drive; clutch on drive shaft
Flywheel
Intermediate gear and pinion
Main gear and pinion
Clutch
(d) Multiple reduction, twin-gear drive; clutch on intermediate shaft

Fig. 2 **Four types of drive-and-clutch arrangements for mechanical presses**

Hydraulic Presses. Hydrostatic pressure against one or more pistons provides the power for a hydraulic press. Most hydraulic presses have a variable-volume, variable-pressure, concentric-piston pump to provide a fast slide opening and closing speed. It also provides a slow working speed at high forming pressure. The principal components of a typical hydraulic press, shown in Fig. 3, include a bolster plate attached to the bed to support the dies and to guide the pressure pins between the die cushion and the pressure pad. The capacity of a hydraulic press depends on the diameter of the hydraulic pistons and on the rated maximum hydraulic pressure, which is a function of the pump pressure and related mechanisms. Hydraulic presses with capacities up to 445 MN (50,000 tonf) have been built, but most are less than 133 MN (15,000 tonf). The typical hydraulic press is rated at 900 kN to 9 MN (100 to 1000 tonf). Gap-frame presses are rated at 345 to 4350 kN (5 to 50 tonf).

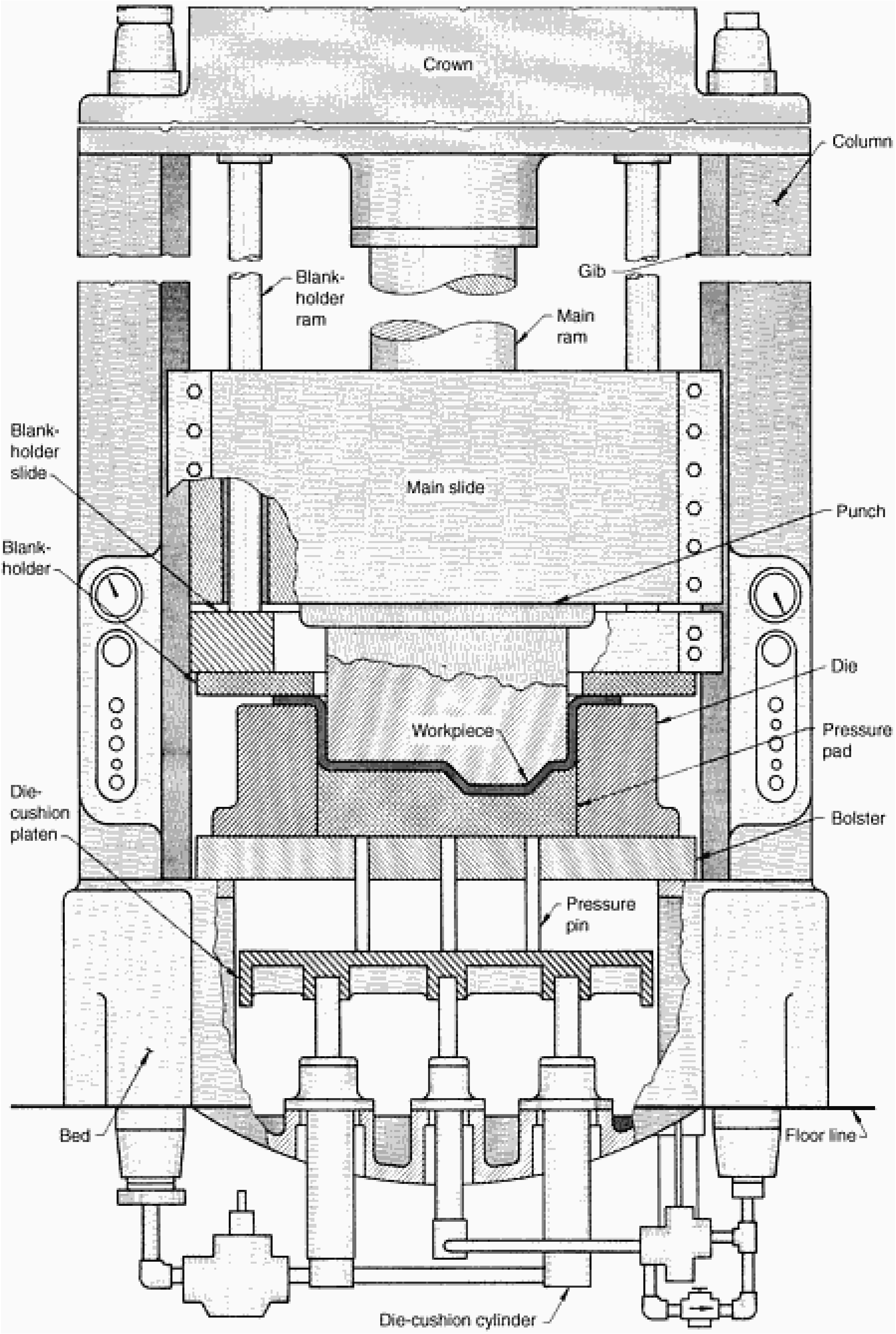

Crown
Column
Gib
Blank-holder ram
Main ram
Blank-holder slide
Main slide
Punch
Blank-holder
Die
Workpiece
Pressure pad
Bolster
Die-cushion platen
Pressure pin
Bed
Floor line
Die-cushion cylinder

Fig. 3 **Principal components of a double-action hydraulic press with a die cushion**

Hydraulic press slides, or platens, are actuated by numerous combinations of hydraulic drives. Hydraulic presses usually have a longer stroke than mechanical presses, and force can be constant throughout the stroke. Hydraulic presses have an adjustable stroke for one or more slides. Accumulators or large-volume pumps can provide fast motion for a slide to open and close. High-pressure pumps provide the working force at a slower speed.

Usually all slides are operated by one pumping system. The relation of each action to the others, interaction, and timing all depend on the controls.

Press Selection

Proper press selection is essential for successful and economical operation. The purchase of a press represents a substantial capital investment, and return on investment depends upon how well the press performs the job required. No general-purpose press exists that can provide maximum productivity and economy for all applications. Compromises usually require the use of a press for more than one job. Consideration should include both present and future production requirements. Important factors influencing the selection of a press include size, force, energy, and speed requirements. The press must be capable of exerting force in the amount, location, and direction, as well as for the length of time, needed to perform the specified operations. Other necessary considerations include the size and geometry of the workpieces, the workpiece material, operations to be performed, number of workpieces to be produced, production rate needed, accuracy and finish requirements, equipment costs, and other factors.

Size, Force, and Energy Requirements. Bed and slide areas of the press must be large enough to accomodate the dies to be used and provide adequate space for die changing and maintenance. Space is required around the dies for accessories such as keepers, pads, cam return springs, and gages; space is also needed for attaching the dies to the press. Shut height of the press, with adjustment, also must be suitable for the dies.

For higher-speed operation, presses should be selected with the shortest stroke possible, thus increasing productivity. Stroke requirements, however, depend upon the height of the parts to be produced. Blanking requires short strokes, but some forming and drawing operations require long strokes, especially for ejection of parts.

Size and type of press to be selected also depend upon the method and direction of feeding, the size of sheet, coil stock, blank, or workpiece to be formed, the type of operation, and the strength and other characteristics of the material being formed. Material or workpiece handling and die accessibility generally determine whether the press should be of gap-frame or straight-side construction, and whether it should be inclined or inclinable. Physical size of a press can be misleading with respect to its capacity. Presses having the same force rating can vary considerably in size depending upon differences in length of stroke, pressing speed, and number of strokes per minute.

The force required to perform the desired operations determines press capacity, expressed in tons or kilonewtons (kN). The position on the stroke at which the force is required and the length of stroke must be considered.

Energy or work (force × distance), expressed in inch-tons or joules (J), varies with the operation. Blanking and punching require the force to be exerted over only a short distance; drawing, forming, and other operations require force application over a longer distance. The major source the flywheel. The energy available increases with the square of the flywheel speed.

Possible problems are minimized by selecting a press that has the proper frame capacity, drive motor rating, flywheel energy, and clutch torque capacity.

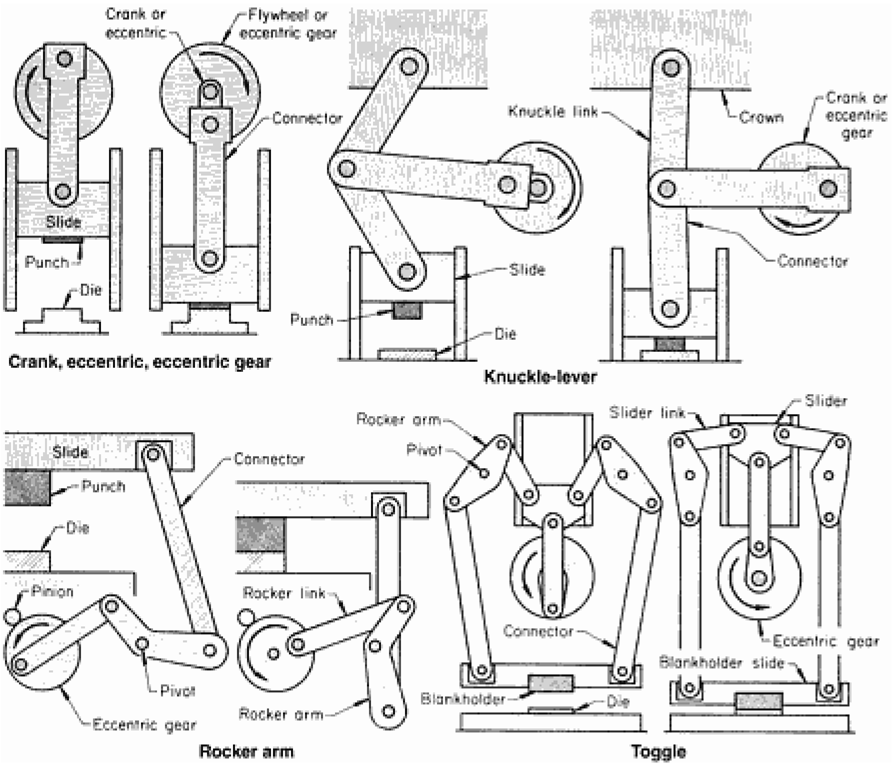
Speed Requirements. Press speed is relative, varying with the point of reference. Fast speeds are generally desirable, but limited by the operations performed, the distances above stroke bottoms where the forces must be applied, and the stroke lengths. High speed, however, is not necessarily the most efficient or productive. Size and configuration of the workpiece, the material from which it is made, die life, maintenance costs, and other factors must be considered to determine the highest production rate at the lowest cost per workpiece. A lower speed may be more economical because of possible longer production runs with less downtime.

Simple blanking and shallow forming operations, however, can be performed at high speeds. Mechanical presses have been built that operate to 2000 strokes/min with 25 mm (1 in.) stroke, but applications at this maximum speed are rare. Speeds of 600 to 1400 strokes/min are more common for blanking, and thick materials are often blanked at much slower speeds. For drawing operations, contact velocities are critical with respect to the workpiece material, and presses are generally operated at slide speeds from 10 to 300 strokes/min, with the slower speed for longer stroke drawing operations.

Mechanical Versus Hydraulic Presses. Mechanical presses are the most frequently used for the blanking, forming, and drawing of sheet metal, but hydraulic presses are being used increasingly. For some applications, hydraulic presses offer certain advantages, and in some cases, they are the only machines that can be used. For example, very high force requirements can only be met with hydraulic presses (Table 2).

Slide Actuation in Mechanical Presses

Rotary motion of the motor shaft on a mechanical press is converted into reciprocating motion of the slides by a crankshaft, eccentric shaft, eccentric-gear drive, knuckle lever drive, rocker arm drive, or toggle mechanism, each of which is discussed below and illustrated in Fig. 4.



Crank or eccentric
Flywheel or eccentric gear
Connector
Slide
Punch
Die
Crank, eccentric, eccentric gear
Knuckle link
Crown
Crank or eccentric gear
Slide
Connector
Punch
Die
Knuckle-lever
Slide
Punch
Die
Connector
Pinion
Pivot
Eccentric gear
Rocker link
Rocker arm
Rocker arm
Rocker arm
Pivot
Slider link
Slider
Connector
Eccentric gear
Blankholder slide
Blankholder
Die
Toggle

Fig. 4 Operating principles of various drive systems for mechanical presses

Crankshafts. The most common mechanical drive for presses with capacities up to 2.7 MN (300 tonf) is the crankshaft drive.

Eccentric Shafts. Similar to crankshafts, the eccentric completely fills the space between the supporting bearings of the press crown, thereby eliminating the deflection commonly caused by the unsupported portion where the crank cheeks normally would be. Eccentric drives often are used in high-speed, short-stroke, straight-side presses with progressive dies.

Eccentric-gear drives are used almost universally for large, straight-side presses that operate at speeds under 50 strokes/min. In place of a crankshaft, an eccentric is built as an integral part of the press drive gear. The eccentric gear permits strokes to as long as 1.3 m (50 in.). However, long strokes usually reduce speeds to only 8 to 16 strokes/min. With the eccentric as part of the gear, accuracy and alignment of the gears determine accuracy of alignment of the slide.

Knuckle Lever Drives. Combining the motions of a crank and knuckle lever to drive the press slide, this drive is limited to operations such as coining or embossing.

Rocker arm drives apply crank or eccentric motion to a rocker arm connected to the press slide. In this mechanism, the linkage is driven by an eccentric gear and a connecting rod. The rocker arm drive is a variation of the knuckle lever drive. However, a press with rocker arm drive is not limited to coining operations; it can also be used for drawing or forming operations.

Toggle mechanisms are the most widely used means of providing the second action in double-action mechanical presses. The toggles operate an outer slide, which clamps the blank against the die, while the punch, operated by the inner slide directly from the crankshaft, performs the draw operation.

Number of Slides

Mechanical (and hydraulic) presses have one, two, or three slides and are referred to as single, double, or triple-action presses. Each slide can be moved in a separately controlled motion. A single-action press has one reciprocating slide (tool carrier) acting against a fixed bed. Presses of this type, which are the most widely used, are used for many different metal-stamping operations, including blanking, embossing, coining, and drawing.

A double-action press has two slides moving in the same direction against a fixed bed. These slides are generally referred to as the outer (blankholder) slide and the inner (draw) slide. The blankholder slide is a hollow rectangle, while the inner slide is a solid rectangle that reciprocates within the blankholder.

A triple-action press has three moving slides: two slides moving in the same direction as in a double-action press and a third, or lower, slide moving upward through the fixed bed opposite in direction to the blankholder and inner slides. This permits reverse drawing, forming, or beading operations against the inner slide while both upper actions are dwelling.

Cycle time for a triple-action press is necessarily longer than for a double-action press because of the time required for the third action.

Auxiliary Equipment

Most primary press operations are automated, allowing equipment for feeding and unloading to be used for fairly short runs. Hand feeding, with its attendant hazards, is often confined to secondary operations on partly completed workpieces. Goals for planning automated operations should include:

- Maximum safety to the operator and to the equipment
- High or nearly continuous production
- Improved quality of the product and minimum scrap
- Reduction in cost of the finished parts

The shape and position of the part before and after each operation must be carefully studied to determine whether design changes, such as adding tabs or extra stock to the blank, will facilitate handling.

Automatic handling equipment can be divided into the following categories: feeding equipment, unloading equipment, and transfer equipment.

Coil-handling equipment moves coiled stock to the press area and uncoils it with a minimum of damage to the stock and minimum danger to the tools and operator. Reliable coil handling is important, because coil stock is increasingly used to supply material to presses. Other auxiliary equipment includes lubricant applicators, stock straighteners, and levelers.

Selection of Die Materials for Sheet Metal Forming

THE USEFUL PERFORMANCE of a forming die is measured in terms of its wear. Total wear is affected primarily by the length of the production run and the severity of the forming operation. Hence, production quantity and forming severity are the most important factors in selecting die materials for forming. The metal being formed, its thickness, and the finish and dimensional tolerances required in the part are also influential factors.

Die Materials

Recommended die materials range from plastics for low reduction of simple to moderate parts, up to the most wear-resistant surface hardened tool steels. Parts of even greater severity, or those run in quantities larger than one million, may require dies or inserts of cemented carbide. Table 3 lists the variety of die materials for press forming operations.

Table 3 Tool materials commonly used for press forming dies

Material	Nominal composition
Tool steels	
W1	Fe-1.0C
S1	Fe-0.50C-1.5Cr-2.5W
O1	Fe-0.9C-1Mn-0.5Cr-0.5Mo
A2	Fe-1C-5Cr-1Mo
A4	Fe-1C-2Mn-1Cr-1Mo
D2	Fe-1.5C-12Cr-1Mo-1V
D3	Fe-2.25C-12Cr
D5	Fe-1.5C-12Cr-1Mo-3Co
D7	Fe-2.35C-12Cr-1Mo-4V
M2	Fe-0.8C-4Cr-5Mo-6W-2V
M4	Fe-1.3C-4Cr-4.5Mo-5.5W-4V
Vanadis 4[a]	Fe-1.5C-8Cr-4V-1.5Mo
Vanadis 10[a]	Fe-2.9C-8Cr-9.8V-1.5Mo
CPM 10V[a]	Fe-2.45C-5Cr-9.75V-1.3Mo
Other ferrous alloys	
Hot-rolled low-carbon steel	Fe-0.10 to 0.20C
Unalloyed cast iron, 185 to 225 HB	Fe-3C-1.6Si-0.7Mn
Alloy cast iron, 200 to 250 HB	Fe-3C-1.6Si-0.4Cr-0.4Mo
Cast high-carbon steel, 185 to 225 HB	Fe-0.75C
Cast alloy steel, 200 to 235 HB	Fe-0.45C-1.1Cr-0.4Mo
4140 alloy steel	Fe-0.4C-0.6Mn-0.3Si-1Cr-0.2Mo
4140 modified	Fe-0.4C-1.2Cr-0.2Mo-1Al
Nonferrous alloys	
Zinc alloy (UNS Z35543)	Zn-4Al-3Cu-0.06Mg
Aluminum bronze (UNS C62500), 270 to 300 HB	Cu-13Al-4Fe
Nonmetals	
Polyester-glass	50% polyester, 50% glass in the form of cloth, strand, or chopped fibers
Epoxy-glass	50% epoxy, 50% glass as above
Polyester-metal	Polyester reinforced with metal powder
Epoxy-metal	Epoxy reinforced with metal powder
Nylon-metal	Polyamide reinforced with metal powder
Polyester or epoxy-glass-metal	Polyester or epoxy with both glass and metal as above

(a) P/M tool steels

A brief review of tool materials for various forming operations is given below. More detailed information on selection of tool and die materials for press forming, deep drawing, spinning, shearing, and slitting, as well as other forming processes, can be found in the *ASM Specialty Handbook: Tool Materials.*

Cast iron is a useful die material for forming parts larger than about 300 mm (12 in.). Its performance makes it suitable for use in medium production runs or short runs of large parts. When cast iron is used with inserts, it will produce greater quantities. Cast iron should have predominantly fine pearlite with no massive carbides and a minimum of ferrite. Graphite should be of type A distribution with a preferred flake size 4 to 5.

The zinc alloy recommended for some sheet forming dies (Table 3) has high pattern fidelity when cast, but requires very accurate shrink patterns to minimize hand labor in finishing. It is economical only for die components at least 300 mm (12 in.) long, and is most economical in dies about 900 mm (36 in.). One of its principal values is for complicated dies that would require intricate machining and hand tooling if made of cast iron, but which can be cast more closely with zinc. In tensile strength, compressive strength, and hardness, zinc tooling alloys are inferior to other metals used in die construction.

Steels. Hot-rolled mild steel plate with carbon content from 0.10 to 0.20% is in major use as a die material for short-run forming of small parts. This type of steel is not recommended without surface hardening except for quantities of less than 10,000 parts. In addition, hot-rolled mild steel can be used for dies where straightening facilities are available for correcting distortion induced by heat treatment.

Several medium-carbon alloy steels such as 4140 are available in plate form and are useful for some types of forming dies. Such steels are generally used for lower production runs.

Cast steel is used for forming parts larger than 300 mm (12 in.) long where the shape of the part makes a casting more feasible than wrought stock. Plain carbon steel (0.65 to 0.85% C) and alloy cast steel (Fe-0.45C-1.1Cr-0.4Mo) are two commonly used compositions. Cast steel is more costly and more difficult to machine than cast iron and is more likely to gall. However, it is tougher than cast iron. One important advantage of cast steel, particularly the plain carbon grade, is its weldability. It can be rewelded with steel or hardfaced with tool steel, aluminum bronze, or other wear-resistant hardfacing alloy. Because of its resistance to galling, it is less desirable for dies used for forming carbon and stainless steels than for aluminum and copper alloys. Cast steel is also useful for restrike, flanging, and other types of dies that are less likely to gall or pick up metal from the sheet.

Tool steels, often nitrided, are used for long production runs (100,000 to one million parts) and for tooling applications requiring long wear life and good toughness. As shown in Table 3, a wide variety of wrought and powder metallurgy grades are used.

Aluminum bronzes are available in a wide range of hardness from 120 to 340 HRB. These alloys have excellent resistance to galling and are desirable for dies where best finish is required on carbon or stainless steel parts.

Cemented Carbides. For long production runs, inserts of sintered tungsten carbide (WC-10Co) are widely used, especially for deep-drawing dies. In dies of about 200 mm (8 in.) or less for continuous production of over one million pieces, cemented carbides have proved to be the most economical die material. Such dies have maintained size in drawing 60% reductions of more than 500,000 pieces and have made as many as one million parts with reductions greater than 40% when the steel to be drawn is surface treated with zinc phosphate and soap. However, cemented carbides are not superior to tool steels (such as D2) in complex deep drawing operations, such as those with reductions greater than 40% which combine drawing with coining or stretching.

Plastics. Even more than with other tooling materials, the quality and economy of plastic tooling improves with shop experience and volume. Polyester, epoxy, phenolic resin, and nylon have been used. Plastic dies of longest life are constructed so that the wearing surface is faced with glass cloth that has had most of the plastic material forced out under pressure before and during curing. Plastics are most economical when a model is available as a pattern for the lay-up of the plastic-impregnated glass cloth facing, which is backed up with chopped glass fibers impregnated with 50% resin. The strength (70 to 275 MPa, or 10 to 40 ksi), and, in particular, the hardness of plastics are inferior to those of metallic die materials. In some instances, the problem of obtaining the required strength in a plastic die must be solved by extra work in designing or developing; but in many cases the regions of high pressure are confined to local areas, which, if anticipated, are strengthened with metal inserts.

Selection and Use of Lubricants in Forming Sheet Metal

LUBRICANTS AND LUBRICATION are relatively inexpensive, yet important and often indispensable for efficient forming of quality parts. In general, the specific characteristics of the surfaces of both the sheet and the dies are critical in the selection of sheet metal lubrication. As such they provide the boundaries between which the lubricant must operate. These surfaces are complex. The chemistry of the surface is not the same as the bulk chemistry of the sheet or tools. The lubricant interacts with an oxide layer of varying complexity; various contaminants may infiltrate the oxide layer (such as oils, gases, acids, and rust preventives); and the surface may be carburized or decarburized, nitrided, or subjected to some other surface treatment, or coated with a polymer or phosphate. Many other surface-chemistry variations are possible. Furthermore, the surface may have residual compressive or tensile stresses from prior processing. The fine structure of the metal surface also may vary with prior history and be quite different from that of the bulk material. The surface roughness also varies in many geometrically significant ways. Interposed between these nonhomogeneous surfaces is a lubricating film that may be quite complex in structure, activity, and wetting ability.

The complexity of the lubricant/metal interface fundamentally affects the lubricant performance by preventing galling or wear of the tooling, as well as tearing, scratching, or imperfect forming to desired dimensions of the sheet metal.

Lubrication Mechanisms

In sheet metal forming, several different lubrication regimes have been identified (Fig. 5).

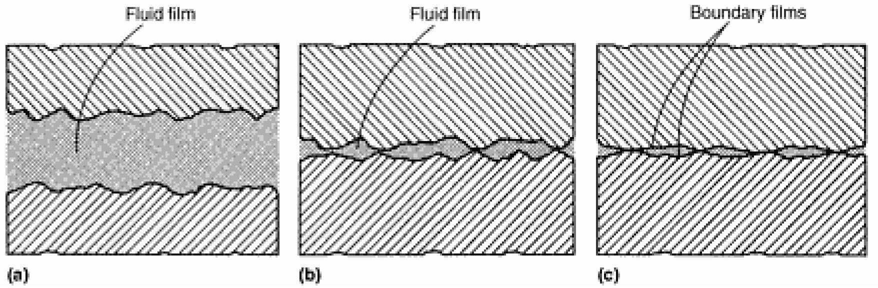


Fig. 5 Three lubrication regimes experienced in sheet metal forming. (a) Thick-film lubrication. (b) Thin-film lubrication. (c) Boundary lubrication

Thick-film (hydrodynamic) lubrication (Fig. 5a) is the occurrence of a thick film of lubricant between tool and workpiece that completely prevents the metal-to-metal contact.

Thin-Film (Quasi-Hydrodynamic) Lubrication. The film between tool and workpiece is thinner, and some metal-to-metal contact takes place (Fig. 5b). This regime occurs in bar and wire drawing and less frequently in sheet metal forming.

Boundary lubrication (Fig. 5c) is typified by metal surfaces separated by a lubricant film only a few molecules thick, with considerable metal-to-metal contact between asperities of the two surfaces. In most forming operations, because of the high pressures and low speeds involved, lubrication is of the boundary type.

Lubricant Forms

The three principle fluids (water, oil, and synthetic fluid) that comprise the primary ingredients of sheet metal forming lubricants are combined with additives to achieve the desired operating characteristics. Table 4 lists the relative effectiveness of four types of lubricants for various functions. Some of the more important additives include emulsifiers, extreme-pressure (EP) additives, thickeners, solid lubricants (e.g., graphite and molybdenum disulfide), antifoaming agents, corrosion inhibitors, and antimicrobial agents.

Table 4 Relative effectiveness of different types of lubricants for various functions

Function	Relative effectiveness[(a)]			
	Compounded oil	**Oil-in-water emulsion**	**Semisynthetic solution**	**Synthetic solution**
Provide lubrication at high pressure (boundary lubrication)	1	2	3	4
Reduce heat from plastic deformation (heat transfer)	5	2	2	1
Provide cushion between workpiece and die to reduce adhesion and pickup (film thickness)	1	2	3	4
Reduce friction between die and workpiece and, thus, heat	1	2	2	1
Reduce wear and galling between tool and workpiece (chemical surface activity)	4	3	2	1
Flushing action to prevent buildup of scale and dirt (fluid flow)	5	4	3	2
Protect surface characteristics; nonstaining	5	2	2	1
Minimize processing costs, welding, cleaning, and painting	5	2	2	1
Minimize environmental effect, air contamination, and water recovery	5	2	2	1

(a) 1, most effective; 5, least effective

Lubricant Selection

Selection of an appropriate lubricant for a specific sheet metal forming operation depends on a number of diverse criteria that must be successfully satisfied:

- Effect of lubricant on the the forming operation (effect on both tool wear and part tolerance and finish)
- Application method and efficiency thereof
- Maintenance of lubricant performance, taking into account problems of recirculation, testing, and disposal
- Corrosion of tooling, machine, and finished parts
- Cleaning
- Welding, painting, or coating of the work material
- Worker response
- Supplier support
- Toxicity and health
- Cost, including cost of lubricant and its effect on overall product cost

Unlike bulk deformation processes such as forging, the temperature increase in sheet metal forming is generally low unless the complexity of deformation and/or the strength of the material is very high. Generally, except in the case of ironing, sheet metal forming involves little or no thickness change. Deformation is generally biaxial in the plane of the sheet. However, there can be considerable relative motion between tool and workpiece. Further, the area of tool contact is often large. Surface finish and part tolerance depend on tool geometry and finish, speed and temperature of deformation, the combination of forming steps required, and the choice and application of lubricant. The type of metal, complexity of part shape, part tolerance, and surface finish specifications all influence the choice of lubricant. Table 5 lists recommended lubricants for various work metals.

Table 5 Lubricants for forming of specific sheet materials

Metal or alloy	Recommended lubricants for:	
	Cold forming	**Hot forming**
Aluminum alloys	Synthetic solutions, emulsions, lanolin suspensions, water suspensions, soap solutions, mineral oil plus fatty oils	Graphite suspension
Copper alloys	Emulsions plus fatty oils, mineral oils plus fatty oils, soap suspensions, water suspensions, tallow suspensions synthetic solutions	Pigmented pastes, graphite suspensions
Magnesium alloys	Solvent plus fatty compounds, mineral oils plus fatty compounds	Graphite plus molybdenum disulfide, soap plus water, tallow plus graphite
Nickel, nickel-base alloys	Emulsions, mineral oils plus EP additives, water plus chlorine additives, conversion coatings plus soap	Graphite suspension, molybdenum disulfide suspension, resin coating plus salts
Refractory metals and alloys	Copper plating	Molybdenum disulfide, graphite suspension
Carbon and low-alloy steels	Emulsions, soap pastes, water, fatty oils plus mineral oils, polymers, conversion coating plus soap, molybdenum disulfide or graphite in grease, synthetic solutions	Graphite suspension
Stainless steels	Fatty oils plus mineral oil, water, polymers, conversion coating plus soap, mineral oil plus EP additives, pigmented soaps	Graphite suspension
Titanium, titanium alloys	Water, pigmented soaps, polymers, conversion coating plus soap	Graphite and molybdenum disulfide suspension

The relationship of many process variables influence the choice of lubricant. These include speed of operation; tool geometry; number and severity of each forming operation; worker exposure to lubricant; fluid makeup; circulation, recycling, and disposal; and the effect of the lubricant film on subsequent operations such as welding, cleaning, and plating. A simple recommendation based on material, tooling, and process may prove to be far from optimum; many other factors can influence lubricant choice. The following discussions for specific materials are guidelines to provide some background in lubricant selection.

Lubricants for Forming Carbon and Alloy Steels

A wide range of lubricants is available for forming steel sheet. The speed of operation and resulting temperature, as well as thickness of stock and complexity of shape, influence lubricant choice. Oil, solvent, and water-base fluids, as well as pastes and gels, may be effective, depending on operating conditions.

Blanking and Piercing. Straight oil, compound oil, or emulsions with sulfur, chlorine, and/or fatty esters are used for most operations. Solutions may be used when the operation is less severe.

Multislide Forming. Light compounded oils and water-base emulsions and solutions with chlorine and fatty additives are used successfully. Care must be taken to prevent buildup on the dies and corrosion of machine or formed parts when water-base lubricants are used.

Deep Drawing. Progressive and multiple-die sets are being used more and more frequently, and thus carry-through of the lubricant becomes more and more important. Multiple-die lubrication sites to provide die lubrication at succeeding stations may be an alternative to ensure adequate lubrication. Compounded oils and emulsions or pastes are used successfully. Chlorinated compounds and fatty esters are commonly chosen additives. Soap-base lubricants are also applied frequently and successfully.

Spinning. Both lubrication and cooling are important effects provided by appropriate lubricant choices. Water-base emulsions and solutions containing chlorinated or sulfochlorinated additives and/or fatty esters are used. Nonpigmented water-base pastes are also effective.

Roll Forming. Water-base emulsions and solutions have been used to form both bare and coated steel. For galvanized steel, white rust can be a problem if water-base lubricants are used and not properly applied and removed. Solvent-base fluids are often preferred, particularly to reduce residue. Light oils also may be used, both compounded and uncompounded with chlorinated compounds, soaps, or fatty esters.

Lubricants for Forming Stainless Steels

In general, stainless steels are more difficult to form than carbon or low-alloy steels because of their higher strength. Chemically reactive lubricants containing sulfur or chlorine must be chosen carefully. Formed parts should be furnace treated after removal of the lubricant film. Sometimes this step may be avoided if high-molecular-weight polymers or complex fats are used in lubricant formulation.

Blanking and Piercing. Solutions and emulsions containing sulfur and/or chlorine are particularly effective for lighter-gage material. Oils compounded with sulfur and/or chlorine are effective in heavier-gage material.

Multiple-Slide Forming. Oil and water-base fluids are successfully used. Recently, solutions with complex esters and fatty compounds have been used to eliminate parts cleaning before use.

Deep Drawing. Because of the high work-hardening characteristics of some stainless steels and attendant high die pressure and temperatures, oils with EP additives such as sulfur, chlorine, and phosphorus are most often the lubricants selected. Pigmented and nonpigmented pastes are often used with or without EP additives.

Roll Forming. Thin-gage sheet may be formed by application of solvent-base as well as water-base fluids at the roller. Thicker material and/or more complex shapes, on the other hand, require oils or emulsions compounded with fatty oils, EP additives, and soaps.

Lubricants for Forming Heat-Resistant Alloys

In general, heat-resistant alloys (complex iron, nickel, and cobalt-base materials) as a class use lubricants that are suitable for stainless steel. Cobalt-base alloys are particularly difficult to form into sheet because of their high strength and relative inertness. Care must be taken to avoid embrittlement by sulfur diffusion in nickel-base alloys. Pigmented lubricants are difficult to remove after forming, and this may discourage their use.

Blanking and Piercing. Soap-base oils and emulsions are used with and without chlorinated additives. Wax and polymer additives may be used if the blanking step is complex.

Spinning. Chlorinated additives in an oil base as well as in emulsions containing fatty esters are effective. Soap-base pastes are also often chosen for application.

Lubricants for Forming Refractory Metals and Alloys

Materials such as molybdenum, tungsten, tantalum, niobium, and their alloys are often warm or hot formed. Forming is most successful, however, at room temperature using metal coatings with application of an auxillary lubricant.

Drawing. Fluorinated complex polymers are used to form tantalum; graphite in fat has been used for forming niobium. Both metals may be formed at room temperature.

Spinning. Molybdenum disulfide in oil or graphite in a soap-base paste is used to spin niobium at room temperatures.

Lubricants for Forming Aluminum and Aluminum Alloys

Aluminum and aluminum alloy sheet may be stained or corroded through the improper choice of lubricant. Aluminum oxides build up during forming and may necessitate cleaning of parts and equipment. The lubricant may contribute to undesirable buildup. Lubricant chemistry differs from the chemistry used in formulating lubricants for steel and refractory metals or high-temperature alloys.

Blanking and Piercing. Oils or compounded oils of light viscosity are used. Compounding additions of fatty esters and chlorinated compounds are frequently chosen. Fatty compounded emulsions, as well as soap-base solutions, are also effective. Oxides may be deposited, however, with some compounded oils and emulsions.

Roll Forming. Solvent-base lubricants containing fatty esters as well as emulsions and solutions are frequently used lubricants. Light viscosity oils also may be used; however, oxides may build up on the rolls. Soap-base lubricants are used with care taken to prevent soap deposits.

Deep Drawing. Viscosity and lubricity are critical attributes of lubricants. Water-base fluids may be used if appropriate fatty additives and/or soap additives are used to provide the required barrier and lubricity. Oils of varying viscosity or dry soap films may be used for more difficult draws. Pastes that are soap- and fat-base have been applied successfully. Progressive draws involving multiple steps should provide frequent lubrication at more than one station.

Spinning. Waxes and soaps are effective. Colloidal graphite suspended in an oil carrier also is used successfully. Cleaning can be difficult depending on the severity of the spinning operation.

Lubricants for Forming Copper and Copper Alloys

These metals can stain or corrode during forming. Lubricants must be formulated to prevent both from taking place.

Multislide Forming. Soap and fat-containing oil and/or water-base lubricants are effective. Solvent-base lubricants containing a fatty ester or an inhibited chlorine-containing compound may be used.

Roll Forming. All classes of lubricants using fatty compounds and/or soap-base additives are used successfully in water, oil, or solvent fluids.

Deep Drawing. Depending on severity of draw, oil or water-base lubricants in fluid or paste form may be effective. Soap and fatty compounds, as well as inhibited chlorine-containing compounds, are commonly used additives.

Lubricants for Forming Magnesium Alloys

Magnesium alloys are most often formed warm or hot. Forming at these elevated temperatures is not normally required for other metals of industrial importance.

Drawing. At temperatures to approximately 120 °C (250 °F), soap-base lubricants, fatty esters, polymer additives in oil and water, and pastes formulated with chlorinated additives are successful lubricant systems. At temperatures in excess of 120 °C (250 °F), the choice of lubricant is restricted to synthetic fluids formulated with soap, fatty esters, and/or chlorinated compounds. Above 230 °C (450 °F), graphite and/or molybdenum disulfide in various carriers are preferred.

Spinning. At elevated temperatures, the synthetic fluids compounded with graphite and/or molybdenum disulfide are applied. Water carriers for the solid lubricants may be preferred to reduce smoke and the possibility of fire.

Lubricants for Forming Nickel and Nickel-Base Alloys

These metals are difficult to wet with lubricants; thus heavy-duty lubricants with exceptional film-priming characteristics are necessary for effective lubrication. On the other hand, lubricants containing sulfur, chlorine, or solid additives such as zinc oxide or lead carbonate can, if not removed from the nickel surface, cause embrittlement of the metal.

Shearing, Blanking, and Piercing. Oils incorporating sulfur or chlorine-containing additives may be used. Water-base lubricants of similar composition may be applied if they are removed as soon as possible after forming to prevent embrittlement. Fatty esters and polymers are frequently used as components of formulated lubricants.

Deep Drawing. Soap-base pastes as well as oils with fatty esters, amides, and/or sulfur and chlorine additives have been used. Emulsions fortified with amides and polymers also have been formulated and applied.

Spinning. Pigmented pastes and chlorinated wax in oils are successful lubricants. Plain waxes and soaps are frequently important components of these lubricants.

Lubricants for Forming Titanium Alloys

Titanium alloys gall because of the affinity of the metal for die materials. Notch sensitivity and embrittlement may also lead to splitting or cracking of formed parts. Cold and warm forming with suitable films can prevent metal-to-metal contact. Frequently, overlays of steel sheet or plastic sheet are used with an auxiliary lubricant.

Deep Drawing. Overlays are often used with oil-base lubricants formulated with chlorinated waxes. Oxidized or phosphated coatings are successful in relatively severe drawing operations at elevated temperatures. Graphite and/or molybdenum disulfide in oil may be used.

Roll Forming. Oils compounded with sulfurized or chlorinated fats are used. Oil or water-soluble polymers may also be added. Chlorinated waxes, high-molecular-weight waxes, or polymers soluble in oil may be effective for relatively moderate deformation.

Spinning. Colloidal graphite and/or molybdenum disulfide blended in oil may be used at temperatures up to approximately 205 °C (400 °F), in addition to chlorinated wax and/or sulfurized fat in oil. At higher temperatures, fillers such as bentonite or mica with graphite and/or molybdenum disulfide formulated into a grease are used successfully.

Blanking of Low-Carbon Steel

A BLANK is a shape cut from flat or performed stock. Ordinarily, a blank serves as a starting workpiece for a formed part; less often, it is the end product. This article will discuss the production of blanks from low-carbon steel (such as 1008 and 1010) sheet and strip in dies in a mechanical or hydraulic press.

Fig. 7 Use of a parting punch to make blanks not having mating adjacent surfaces

Blanking. Also called punching, blanking is used to cut a complete outline of a workpiece in a single press stroke. Because a scrap skeleton is usually produced, blanking involves some material waste. However, blanking is usually the fastest and most economical way to make flat parts, particularly in large quantities.

Piercing. Also called punching or perforating, piercing (with a flat-end punch), is similar to blanking except that the punched-out (blanked) slug is the waste and the surrounding metal is the workpiece. (See "Piercing of Low-Carbon Steel" in this article.)

Notching. In notching, the individual punch removes a piece of metal from the edge of the blank or strip (Fig. 8).

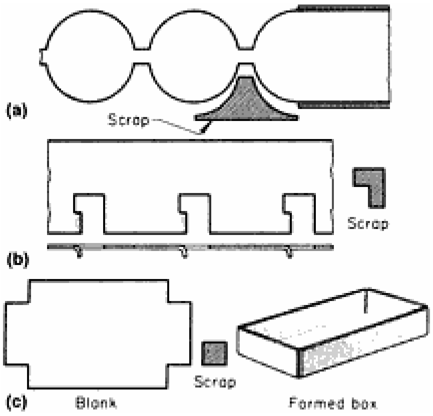


Fig. 8 Notched work illustrating the use of notching for freeing metal (a) before drawing and (b) before forming and for (c) removing excess metal before forming

Die Clearance

The terms clearance, die clearance, and punch-to-die clearance are used synonymously to refer to the space between punch and die. Clearance is important for the reliable operation of the blanking equipment, the quality and type of cut edges, and the life of the punch and die.

Relief in a blanking die (Fig. 9) is the taper provided to allow the severed blank to fall free. The relief angle may range from $\frac{1}{2}$° to 2° from the vertical wall of the die opening. Relief is sometimes called draft or angular clearance. In some dies, the relief may start at the top of the die surface and have a taper of only 0.002 mm/mm (0.002 in./in.) per side. Some dies have a straight, vertical wear land between the top of the die and the relief.

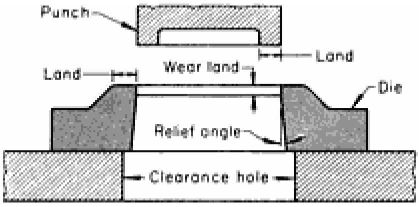


Fig. 9 Relief in a blanking die

Piercing of Low-Carbon Steel

PIERCING is the process of cutting holes in sheet metal, generally by removing a slug of metal, with a punch and die. Piercing is similar to blanking, except that in piercing the work metal that surrounds the piercing punch is the workpiece and the punched-out slug is scrap, while in blanking the workpiece is punched out.

Ordinarily, piercing is the fastest method of producing holes in steel sheet or strip. Generally, it is the most economical method for medium-to-high production. Pierced holes can be almost any size and shape; elongated holes are usually called slots. The accuracy of conventional tool steel or carbide dies provides pierced holes with a degree of quality and accuracy that is satisfactory for a wide variety of applications.

Characteristics of Pierced Holes

Pierced holes are different from through holes produced by drilling or other machining methods. A properly drilled or otherwise machined through hole has a straight sidewall for the full thickness of the work metal, with a high degree of accuracy in size, roundness, and straightness. The sidewall of a pierced hole is generally straight and smooth for only a portion of the thickness, beginning near the punch end of the hole; the rest of the wall is broken out in an irregular cone beyond the straight portion of the hole, producing fracture, break-out, or die break (see Fig. 10).

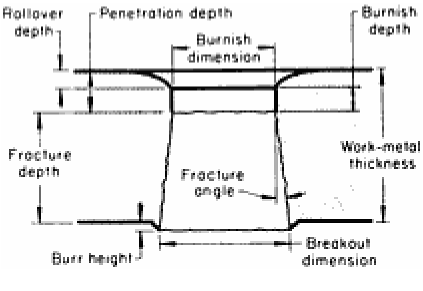


Fig. 10 Characteristics of a pierced hole. Curvature and angles are exaggerated for emphasis.

Piercing typically begins as a cut that produces a burnished surface on the hole wall and some rollover (a curved surface caused by deformation of the workpiece before cutting begins) as shown in Fig. 10. The punch completes its stroke by breaking and tearing away the metal that was not cut during the beginning of the piercing operation.

Selection of Die Clearance

Clearance, or the space between the punch and the sidewall of the die, affects the reliability of piercing equipment, the characteristics of the cut edges, and the life of the punch and die. Published recommendations for clearances have varied widely, with most suggesting a clearance per side of 3 to 12.5% of the stock thickness for steel.

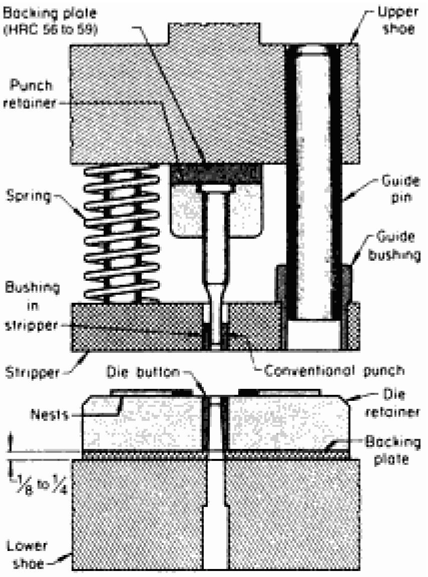
Establishment of the clearance to be used for a given piercing or blanking operation is influenced by the required characteristics of the cut edge of the hole or blank and by the thickness and the properties of the work metal. Larger clearances prolong tool life. An optimal clearance can be defined as the largest clearance that will produce a hole or blank having the required characteristics of the cut edge in a given material and thickness. Because of differences in cut-edge requirements and in the effect of tool life on overall cost, clearance practices vary among plants and for different applications.

Presses

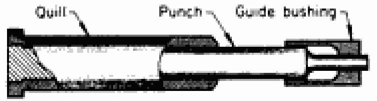
Presses used in piercing are the same as those used in other pressworking operations. Open-back gap-frame presses of the fixed upright, fixed inclined, or inclinable type are common. The stock can be fed from the side with minimal interference from the press frame, and the parts can be removed from the front by the operator or ejected out the back by gravity or air jets.

Tools

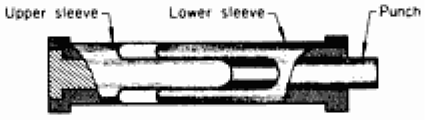
A typical piercing die consists of upper and lower die shoes, to which punch and die retainers are attached; punches and die buttons; and a spring-actuated guided stripper (Fig. 11). Small workpieces are generally pierced in compound dies that blank and pierce in the same stroke. Piercing is also done in the stations of a progressive die or a transfer die. Any of these dies can be constructed as multiple dies, in which two or more workpieces are pierced at each stroke of the press.


Backing plate (HRC 56 to 59)
Upper shoe
Punch retainer
Spring
Guide pin
Guide bushing
Bushing in stripper
Stripper
Die button
Conventional punch
Nests
Die retainer
Backing plate
1/8 to 1/4
Lower shoe

(a) Piercing-die assembly, with conventional punch


Quill
Punch
Guide bushing

(b) Standard quill punch


Upper sleeve
Lower sleeve
Punch

(c) Telescoping - sleeve quill punch

Fig. 11 Layout of a typical piercing die, and three types of punches used

Figure 11 shows the three types of punches used for piercing: conventional, standard quill, and telescoping-sleeve quill. Conventional punches are generally available with a standard maximum shank diameter of 25 mm (1 in.). They can be used to pierce round, square, oblong, or rectangular holes with size and shape not exceeding 25 mm (1 in.) in diameter or a size and shape that can be machined or ground on the end of the shank.

Fine-Edge Blanking and Piercing

FINE-EDGE BLANKING (also known as fine blanking) produces precise blanks in a single operation with smoother edges and closer tolerances than possible with conventional blanking. In fine-edge blanking, a V-shaped impingement ring (Fig. 12) is forced into the stock to lock it tightly against the die. The ring also forces the work metal to flow toward the punch, so that the part can be extruded out of the strip without fracture or die break. Die clearance is extremely small, and punch speed is much slower than in conventional blanking.

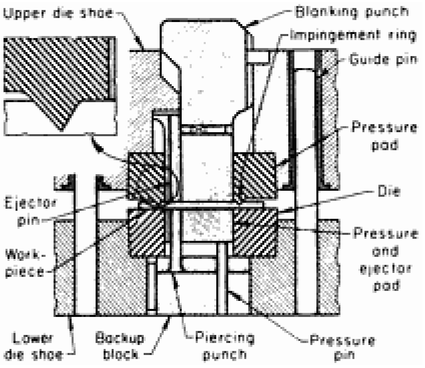

Upper die shoe
Blanking punch
Impingement ring
Guide pin
Pressure pad
Die
Ejector pin
Work-piece
Pressure and ejector pad
Lower die shoe
Backup block
Piercing punch
Pressure pin

Fig. 12 Typical tooling setup for fine-edge blanking a simple shape

Fine-edge piercing is performed either separately or at the same time as fine-edge blanking. In piercing small holes, an impingement ring may not be needed.

No further finishing or machining is necessary to obtain blank or hole edges comparable to machined edges, or to those that are conventionally blanked or pierced and then shaved. A quick touch-up on an abrasive belt or a short treatment in a vibratory finisher may be used to remove the small burr on the blank. Specially designed single-operation or compound blanking and piercing dies are generally used for the process.

Comparison with Conventional Blanking

Fine-edge blanking and piercing (Fig. 13) are actually more akin to cold extrusion than to a cutting operation. They are similar to conventional blanking using a compound die but with several important differences. First, fine-edge blanking and piercing use the V-shaped impingement ring. Second, they involve the independent control of the three forces acting on the workpiece (clamping, counterpressure, and blanking) obtained through the use of a triple-action press.

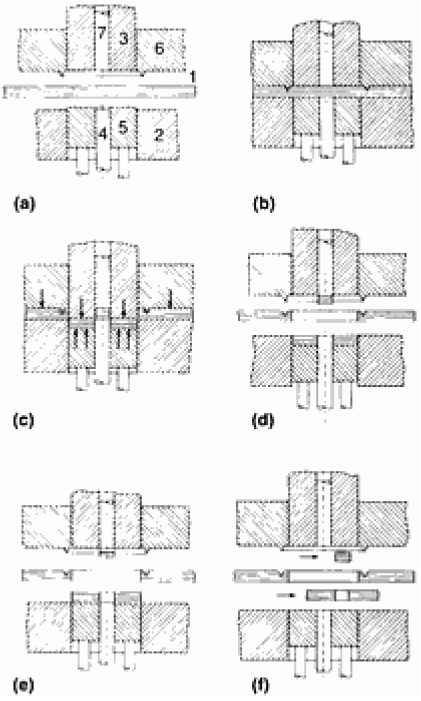

7
3
6
1
4
5
2
(a)
(b)
(c)
(d)
(e)
(f)

Fig. 13 The fine-edge blanking process. (a) Work material is fed into the die. 1, work material; 2, die plate; 3, punch; 4, piercing punch; 5, ejector/counterpunch; 6, impingement ring; 7, slug ejector. (b) The die closes, and the V-shaped impingement ring is embedded into the work material. (c) The part is blanked. The

impingement ring maintains pressure while blanking pressure and counterpressure are exerted against the part. (d) Slugs are ejected from the top down. (e) Part is ejected from the bottom up by reversing counterpressure. (f) Parts and slugs are removed from the die area.

The very small clearance between punch and die is another difference between fine-edge blanking and conventional blanking. Combined with correspondingly tighter tolerances on both punch and die and the fact that the punch enters the die only a slight amount if at all, this feature prevents cracking of the workpiece and results in smooth blanked and pierced edges.

Process Capabilities

Holes with diameters as small as 50% of stock thickness can be pierced in low-carbon steel. In high-carbon steel, the smallest hole diameter is about 75% of stock thickness. Holes can be spaced as close to each other, or to the edge of the blank, as 50 to 70% of stock thickness. Total tolerances obtainable are 0.013 mm (0.0005 in.) on hole diameter and for accuracy of blank outline; 0.025 mm (0.001 in.) on hole location with respect to a datum surface; and 0.025 mm (0.001 in.) on flatness.

No die break shows on the sheared surface of the hole. Blank edges may be rough for a few thousandths of an inch of thickness on the burr side of the part when the width of the part is about twice the stock thickness or less. Finish on the sheared edge is governed by the condition of the die edge and the land within the die. Parts fine-edge blanked from stainless steel will have a surface finish of 0.8 μm (32 μin.) or better. Smooth edges also are produced on spheroidize-annealed steel parts. Burr formation increases rapidly during a run, necessitating frequent grinding of the cutting elements.

Chamfers can be coined around holes and on edges. Forming near the cut edge, or forming offset parts with a bend angle up to 30° is possible under restricted conditions. Metals up to 3.18 mm ($\frac{1}{8}$ in.) thick having a tensile strength of 586 to 793 MPa (85 to 115 ksi) are easily blanked. Parts up to 13 mm ($\frac{1}{2}$ in.) thick can be blanked if press capacity is available. Material thicker than 3.18 mm ($\frac{1}{8}$ in.), especially steel having a carbon content of 0.25% or more, requires an impingement ring on the die so that the corners on the part will not break down. The edges of parts made of 1018 steel work harden as much as 7 to 12 points HRC during blanking. The cutting speed for fine-edge blanking is 7.6 to 15.2 mm/s (0.3 to 0.6 in./s).

Work Materials

Carbon and Alloy Steels. The easiest materials to fine-edge blank are low-carbon steels (<0.25% C). Thin parts, however, have been fine-edge blanked from plain carbon steels containing up to about 0.95% C. Alloy steels can be fine-edge blanked only in the fully annealed, spheroidized condition.

Stainless Steels. Austenitic stainless steels, such as AISI types 301 to 304 and 316, can be fine-edge blanked in the fully annealed condition. These materials, as well as the ferritic type 430 and martensitic type 416 (both fully annealed), have good blanked edges but cause higher tool wear than do plain carbon steels.

Aluminum. Most aluminum alloys, with the exception of alloy 2024, can be fine-edge blanked in the O (annealed) temper. Wrought alloys of the 1*xxx*, 3*xxx*, and 5*xxx* series can be fine-edge blanked in the H (strain hardened) temper with excellent results. In thinner gages, alloys 6061 and 7075 can be fine-edge blanked in the T3 or T4 condition.

Copper. Copper alloys are easily fine-edge blanked. The most workable alloys, such as alloy C27400 (yellow brass, 63%) can be fine-edge blanked even in the full hard condition. Other brasses, such as C26000 (cartridge brass, 70%) and C26800 (yellow brass, 66%) can be worked in the annealed, quarter-hard or half-hard condition. Beryllium copper alloys can be fine-edge blanked in the annealed condition, as can pure copper, soft bronzes, Monel alloys, nickel-silvers, silvers, and gold.

Tools

The design of tools for fine-edge blanking is based on the shape of the part, the method of making the die, the required load, and the extremely small punch-to-die clearance. The considerable loading and required accuracy dictate that the press tools be sturdy and well supported to prevent deflection. The small clearance presupposes precise alignment of the punch and die.

Design. A basic tool consists of three functional components: the die, the punch, and back-pressure components. To produce high-quality blanks, the punch-to-die clearance must be uniform along the entire profile and must be suitable for the thickness and strength of the work metal. Clearance varies between 0.005 and 0.01 mm (0.0002 and 0.0004 in.).

Some diemakers put a small radius on the cutting edge of the die. This causes a slight bell-mouth condition, which produces a burnishing action as the blank is pushed into the die, improving the edge finish.

Blanking and Piercing of Electrical Steel Sheet

ELECTRICAL STEELS are used for various static and rotating electrical devices. They are magnetically soft materials; that is, they are not permanent magnets but have properties that make them useful in electrical applications. Most of the parts produced from electrical steels must be laminated. A lamination consists of flat blanked sheets of a particular shape that are stacked to a given height and fastened together by riveting, bolting, or welding. Electrical steel sheet is available in coils or cut-to-length. For most applications, stock thickness ranges from 29 to 24 gage (0.343 to 0.607 mm, or 0.0135 to 0.0239 in.).

Flat laminations are blanked and pierced from electrical sheet. Laminations can range in diameter from less than 25 mm to 1.3 m (1 to 50 in.) or more (Fig. 14a). Others (Fig. 14b) can range in length from less than 25 to 305 mm (1 to 12 in.) or more.

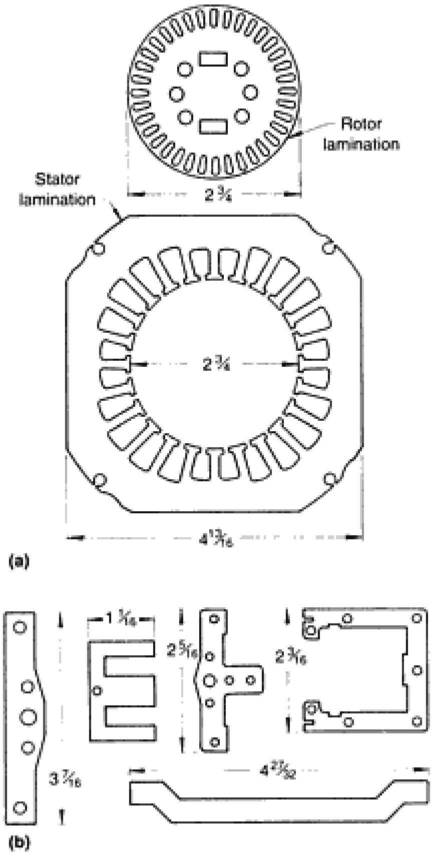


Fig. 14 Typical laminations blanked and pierced from electrical sheet. (a) Laminations for rotating electrical machinery are blanked and pierced in single-station dies (Fig. 15) or progressive dies (Fig. 16). Slots can also be made in precut blanks, one at a time, with notching dies. (b) Typical laminations blanked and pierced from

electrical sheet for application in units other than rotating machines. Dimensions given in inches

Material used for electrical sheet can be classified in the following order with respect to decreasing ease of blanking, piercing, and notching: conventional flat-rolled low-carbon steels such as 1008, nonoriented silicon steels, and oriented silicon steels.

Presses

A general-purpose punch press in good mechanical condition is acceptable for stamping laminations, but large-volume production of laminations by progressive-die methods requires the use of high-productivity presses.

Dies

Single-station and progressive dies are both used for making laminations.

Single-Station Dies. Each single-station die performs one operation, and a set of dies for a lamination can be mounted in one press or in different presses. Simple laminations (Fig. 14) are usually produced in one operation. More complex parts may require several operations. Figure 15 shows a typical sequence for the production of stator and rotor laminations in four operations.

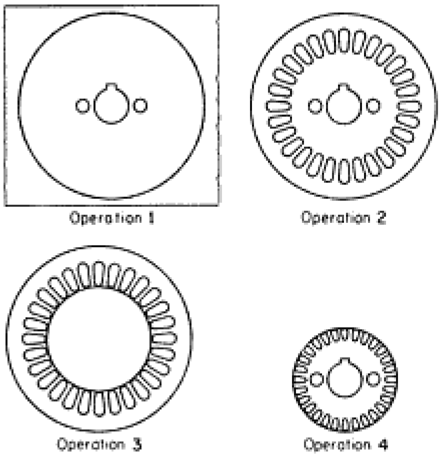


Fig. 15 Sequence of operations for producing stator and rotor laminations using single-station dies. Operation 1, stock blanked and pierced; operation 2, stator lamination notched; operation 3, rotor lamination separated from stator lamination; operation 4, rotor lamination notched. Compare with Fig. 16.

Single-station dies can be used for punching any lamination, regardless of size, composition, shape or quality requirements. However, because production with single-station dies is relatively slow, the cost per piece is high for mass production.

Progressive Dies. Laminations can be produced in large quantities at a lower cost in progressive dies. Progressive dies perform a series of operations at two or more die stations during each stroke of the press. Each working, or active, station in the die performs one or more operations. The work material progresses through successive stations until a completed part is produced (Fig. 16). Idle stations, in which no work is performed, are added to provide strength to the die, to facilitate material travel through the die, to simplify construction, or to increase flexibility for die changes.

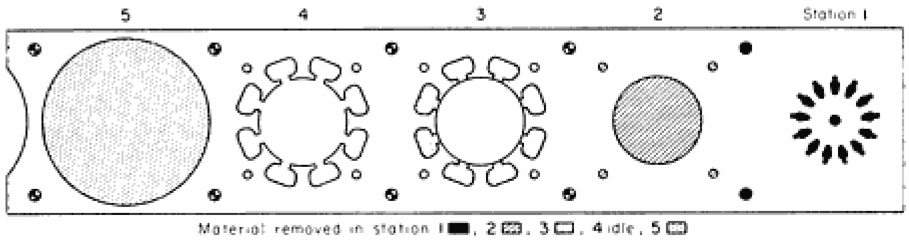


Fig. 16 Blanking and piercing sequence for rotor and stator laminations in a five-station progressive die. Two pilot punches were used at each station. Station 1, pierce pilot holes, rotor slots, and rotor-shaft hole; station 2, pierce stator rivet holes and blank rotor; station 3, pierce stator slots; station 4, idle; station 5, blank stator. Compare with Fig. 15.

Press Bending of Low-Carbon Steel

PUNCH PRESSES are used for bending, flanging, and hemming low-carbon steel when production quantities are large, when close tolerances must be met, or when the parts are relatively small. Press brakes are ordinarily used for small lots, uncritical work, and long parts.

To estimate the press capacity needed for bending in V-dies, the bending load in tons can be computed from:

$$L = \frac{lt^2kS}{s}$$

where L is press load, in tons; l is length of bend (parallel to bend axis), in inches; t is work-metal thickness, in inches; k is a die-opening factor (varying from 1.2 for a die opening of $16t$ to 1.33 for a die opening of $8t$); S is tensile strength of the work metal, in tons per square inch; and s is width of die opening, in inches.

For U-dies, the constant k should be twice the values shown above.

Bendability and Selection of Steels

Temper of the metal affects bendability. Figure 17 shows the types of bends for which the standard AISI tempers of cold-rolled carbon steel strip are suited. Stock of No. 1 temper is not recommended for bending, except to large radii. Stock of No. 2 temper can be bent 90° over a radius equal to strip thickness, perpendicular to the rolling direction. Stock of No. 3 temper can be bent 90° over a radius equal to strip thickness, parallel to the rolling direction; it can also be bent 180° around a strip of the same thickness when the bend is perpendicular to the rolling direction. Stock of No. 4 or No. 5 temper can be bent 180° flat on itself in any direction. The No. 5 temper stock may develop stretcher strains and should not be used if these markings are objectionable.

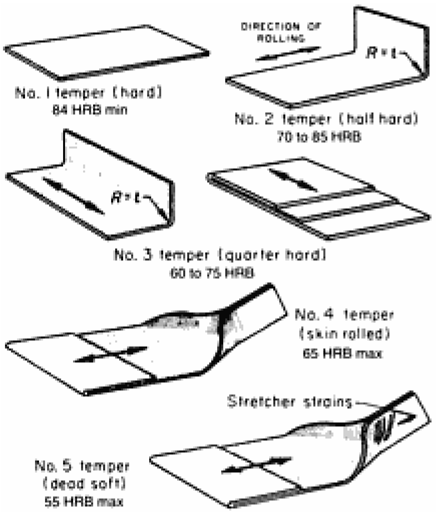


Fig. 17 The most severe bend that can be tolerated by each of the standard tempers of cold-rolled carbon steel strip. Stock of No. 1 (hard) temper is sometimes used for bending to large radii; each lot should be checked for suitability, unless furnished for specified end use by prior agreement. Hardnesses shown are for steel containing 0.25% C (max) in the three hardest tempers and 0.15% C (max) in the No. 4 and 5 tempers. Hardness for No. 1 temper applies to thicknesses of 1.8 mm (0.070 in.) and greater; for thinner sheet, hardness would be a minimum of 90 HRB.

Minimum Bend Radius. Carbon content, quality, and temper of some grades of carbon steel strip and sheet determine minimum bend radius. This is especially true of hot-rolled steel, for which a change from commercial quality to drawing quality reduces minimum bend radius by 33 to 50%. Low-carbon steels of commercial quality are suitable for 90 and 180° bends.

Alloy composition also determines minimum bend radii for common grades of carbon and low-alloy steels. High-strength low-alloy steels, because of their higher yield strength and lower ductility, are more difficult to bend than plain carbon steels--requiring more power, greater bend radii, more die clearance, and greater allowance for springback. It may be necessary to remove shear burrs and to smooth corners in the area of the bend. Whenever possible, the axis of the bend should be across the direction of rolling. If the bend axis must be parallel with the rolling direction, it may be necessary to use cross-rolled material, depending on the severity of the bend.

Effect of Edge Condition on Minimum Bend Radius. For low-carbon steel, the condition of the edge perpendicular to the bend axis has little effect on the minimum bend radius. Steels that are susceptible to work hardening or hardening by heating during gas or electric-arc cutting may crack during bending because of edge condition. For these steels, burrs and hardened edge metal in the bend area should be removed to prevent fracture. Edges can be prepared for bending by grinding parallel with the surface of the sheet and removing sharp corners in the bend area by radiusing or chamfering.

If the burr side is on the inside of the bend, cracking is less likely during bending. This is important on parts with small bend radii in comparison with the metal thickness and on parts with metal thickness greater than 1.6 mm ($\frac{1}{16}$ in.), because fractures are likely to start from stress-raising irregularities in the burr edge if it is on the outside of the bend.

Effect of Metal Thickness on Minimum Bend Radius. Minimum bend radii are generally expressed in multiples or fractions of the thickness of the work metal. On parts that require a minimum flange width or a minimum width of flat on the flange, stock thickness will limit both of these dimensions. If thickness is not critical in the design, the use of thinner stock can make the bending of small radii and narrow flanges feasible.

Hot bending is necessary when the product shapes are too complex or when bend radii are too small for cold forming. The high-strength low-alloy steels can be successfully hot bent at temperatures as low as 650 °C (1200 °F); however, when maximum bendability is needed, temperatures of 845 to 900 °C (1550 to 1650 °F) are recommended. Cooling in still air from these temperatures returns the material nearly to the as-rolled mechanical properties.

Die Construction

The same types of bending dies as those used in press brakes can generally be used in presses. However, there are major differences:

- Because presses ordinarily are not long and narrow like press brakes, more consideration must be given to clearance for removing the finished workpiece when the press is open, as well as clearance for the legs of the bend when the piece is being formed. The bed dimensions of a press also limit the size of workpiece that can be bent.
- Presses cycle rapidly, and shut height is not as easy to change; therefore, fewer pieces are bent in air. More frequently, pieces are formed by bottoming the dies. This has the advantage of decreasing springback.
- Presses are usually used for workpieces less than 610 mm (2 ft) long, and press brakes for pieces longer than 610 mm (2 ft). However, the automotive industry bends very large sheet metal structural members on large presses.

V-dies are composed of a V-block for a die and a wedge-shaped punch (Fig. 18a). The width of the opening in the V is ordinarily at least eight times the stock thickness. In bending, the workpiece is laid over the V in the die, and the punch descends to press the workpiece into the V to form the bend.

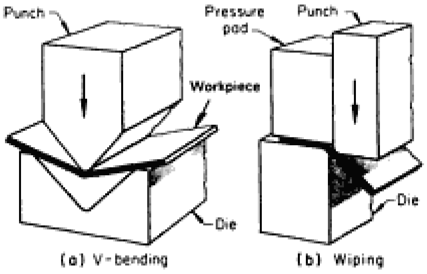


Fig. 18 Bending in a V-die and a wiping die

Wiping Dies. In the wiping die, Fig. 18(b), a pressure pad that is either spring loaded or attached to a fluid cylinder clamps the workpiece to the die before the punch makes contact. The punch descends and wipes one side of the workpiece over the edge of the die. The bend radius is on the edge of the die.

Interchangeable V-Dies. To produce various sizes of V-bends in a punch press, four different sizes of punches can be mounted into the punch holder, which is attached to the press slide. In operation, the groove in the die that gives the needed bend is aligned with the punch, and the die is then fastened to the bolster plate on the press bed. Adjustable side and end stops can be used to position the blanks for bending.

U-Bending Dies. U-shaped pieces can be bent in a die. The width of the U is adjustable by means of spacers and by changing the width of the knockout. Punches can be mounted in the press with a holder similar to that for a V-die and can be provided to the proper width and shape to make either a U or a channel shape.

Rotary-bending dies (Fig. 19) are used to make bends or twists in bars or strip. They rely on cam action to rotate the workpiece. The strip metal is twisted 90° to make a connecting link. The punch is made in two major parts: a hollow cylinder that is solidly mounted to the ram, and inside it, a solid cylinder that is free to rotate. In the inner cylinder, a 90° helical cam groove in its cylindrical surface engages a hardened pin in the outer cylinder.

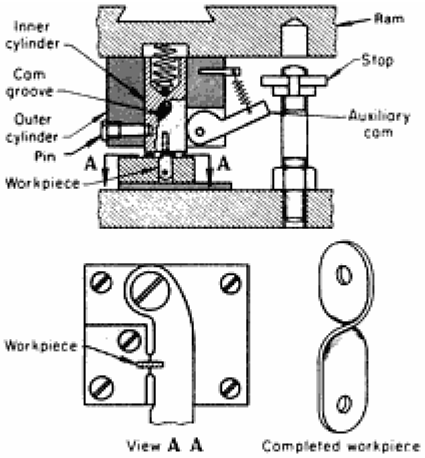


Fig. 19 Rotary bending die used for 90° twisting of strip metal. Die is shown in closed position; inner cylinder has rotated to give workpiece a 90° twist. The auxiliary cam prevents rotation of the inner cylinder until it is free of workpiece.

When the ram descends, a slot in the face of the inner cylinder engages the end of the workpiece. After the inner cylinder bottoms, as the ram continues to move down, the spring compresses, moving the outer cylinder down over the inner cylinder. The action of the pin in the groove makes the inner cylinder rotate, giving the workpiece a 90° twist.

Lubrication

Lubrication is less important for most bending operations than for other types of forming. In many bending operations, no lubricant is used; in others, the mill oil remaining on the stock or a light mineral oil applied before forming is sufficient to prevent galling.

Exceptions to this practice are hole flanging, compression and stretch flanging, and severe bending in which wiping, ironing, or drawing of the work metal may call for more effective lubrication.

Press-Brake Forming

IN PRESS-BRAKE FORMING, the workpiece is placed over an open die. It is then pressed down into the die by a punch actuated by the ram portion of a machine called a press brake. The process is most widely used to form relatively long, narrow parts that are not adaptable to press forming and for applications in which production quantities are too small to warrant the tooling cost for contour roll forming.

Simple V-bends or more intricate shapes can be formed in a press brake. Operations such as blanking, piercing, lancing, shearing, straightening, embossing, beading, wiring, flattening, corrugating, and flanging can be formed in a press brake.

press-brake forming, as in other forming processes, when a bend is made, the metal on the inside of the bend is compressed or shrunk, and that on the outside of the bend is stretched. The applied forces create a strain gradient across the thickness of the work metal in the area of die contact. Tensile strain occurs in the outer fiber, and compressive strain in the inner fiber; both decrease in magnitude toward the neutral axis.

The setup and tooling for press-brake forming are relatively simple (Fig. 20). The distance the punch enters the die determines the bend angle and is controlled by the shut height of the machine. The span width of the die, or the width of the die opening, affects the force needed to bend the workpiece. The minimum width is determined by the thickness of the work and sometimes by the punch-nose radius. After the tools have been set up and the shut height has been adjusted, the press brake is cycled, and the work metal is bent to the desired angle around the nose radius of the punch.

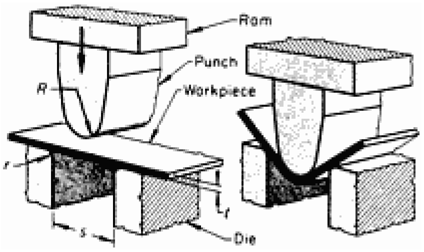


Fig. 20 Typical setup for press-brake forming in a die with a vertical opening. *B*, punch radius; *s*, span width; *r*, die radius; *t*, metal thickness

Applicability

Press-brake forming is most widely used for producing shapes from ferrous and nonferrous metal sheet and plate. Although sheet or plate 6.4 mm ($\frac{1}{4}$ in.) thick or less is most commonly formed in a press brake, metals up to 25 mm (1 in.) thick have often been used.

Workpiece Dimensions. The length of plate or sheet that can be bent is limited only by the size of the press brake. For example, a 5350 kN (600 tonf) press brake can bend a 3 m (10 ft) length of 19 mm ($\frac{1}{4}$ in.) thick low-carbon steel plate to a 90° angle, with an inside radius of the bend equal to stock thickness. If the included angle of the bend is greater than 90°, if the bend radius is larger than stock thickness, or if the length of bend is less than the bed length, a press of correspondingly lower capacity can be used.

Work Metals. Press-brake forming is applicable to any metal that can be formed by other methods, such as press forming and roll forming. Low-carbon steels, high-strength low-alloy steels, stainless steels, aluminum alloys, and copper alloys are commonly formed in press brakes. High-carbon steels and titanium alloys are less frequently formed in a press brake, because they are more difficult to form.

Press Brakes

The primary advantages of press brakes are versatility, the ease and speed with which they can be changed over to a new setup, and low tooling costs. A press brake is basically a slow-speed punch press that has a long, relatively narrow bed and a ram mounted between end housings (Fig. 21). Rams are actuated mechanically or hydraulically.

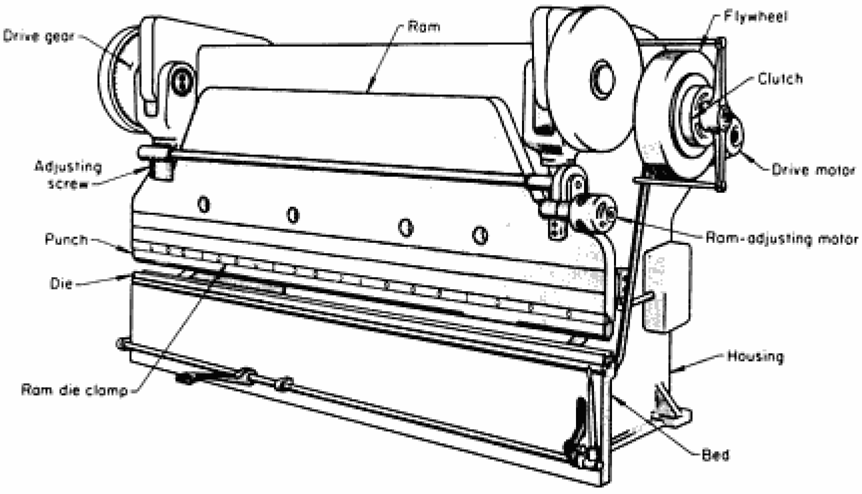


Fig. 21 Principal components of a mechanical press brake

Mechanical Press Brakes. The ram of a mechanical press brake is actuated by a crank or an eccentric through a gear train with a clutch and a flywheel. The gear train is usually designed to provide fast movement of the ram. Shut height (the distance between ram and bed at the bottom of the stroke) is adjustable by means of a screw (usually powered) in the pitman, or link, at each end of the ram. The length of the ram stroke, however, is constant.

Hydraulic Press Brakes. The ram of a hydraulic press brake is actuated by two double-acting cylinders, one at each end of the ram. Force supplied by the hydraulic mechanism will not exceed the press rating; therefore, it is almost impossible to overload a hydraulic press brake. (When thicker metal is inadvertently used, the ram stalls.) Therefore, frames can be lighter and less costly than those for mechanical press brakes, which are subject to overloading.

Hybrid Press Brake. The hydraulic-mechanical hybrid consists of a mechanical press brake driven by a rotary hydraulic motor. Containing a vane that rotates 270° between stops, the rotary hydraulic motor has replaced the piston used in a hydraulic cylinder. As it moves between the two stops, the motor propels the eccentric shaft through the complete cycle, driving the ram to the stroke bottom and back to the top. The hybrid press brake combines the best features of both mechanical and hydraulic press brakes. It offers the same accuracy and operating speeds obtainable with the mechanical press brake while providing the adjustable length and controllability of the hydraulic press brake.

Dies and Punches

V-bending dies and their corresponding punches (Fig. 22a-d) are the tools most commonly used in press-brake forming. The width of the die opening is usually a minimum of eight times the thickness of the work metal (8*t*). The nose radius of the punch should not be less than 1*t* for bending low-carbon steel, and it must be increased as the formability of the work metal decreases. The radius of the V-bending die must be greater than the nose radius of the punch by an amount equal to or somewhat greater than the stock thickness to allow the punch to bottom.

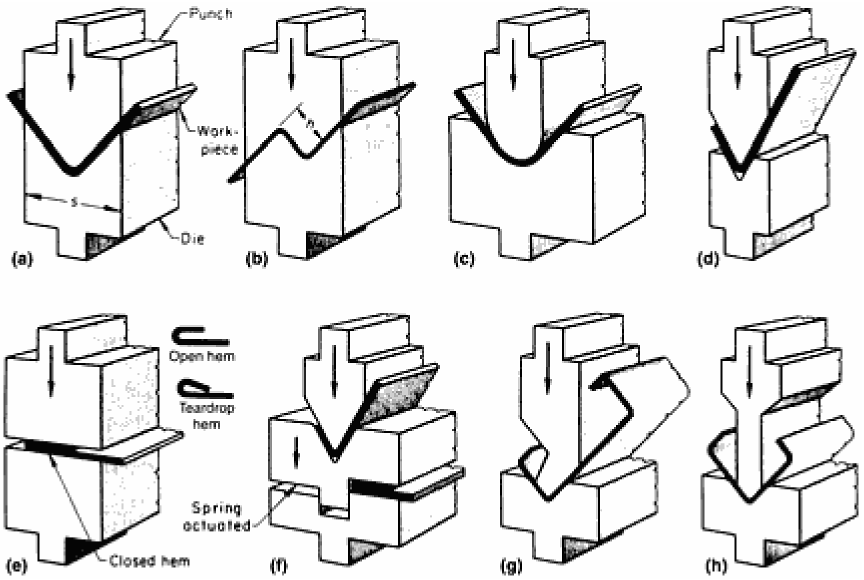


Fig. 22 Dies and punches most commonly used in press-brake forming. (a) 90° V-bending. (b) Offset bending. (c) Radiused 90° bending. (d) Acute-angle bending. (e) Flattening, for three types of hems. (f) Combination bending and flattening. (g) Gooseneck punch for multiple bends. (h) Special clearance punch for multiple bends

Offset Dies. Punch and die combinations like the one shown in Fig. 22(b) are often used to produce offset bends. Because an offset bend requires about four times as much force as a 90° V-bend, offset bending is usually restricted to relatively light-gage metal (3.2 mm, or $\frac{1}{8}$ in., or less). The depth of offset (*h* in Fig. 22b) should be a minimum of six times the work metal thickness to provide stability at the bends.

Radius forming is done with a 90° die and a punch, each having a large radius (Fig. 22c). When the punch is at the bottom position, the inside radius of bend in the workpiece conforms to the radius of the punch over a part of the curve.

The harder the punch bottoms, the more closely the work metal wraps around the punch nose, resulting in a smaller radius of bend and less springback. Uniformity of bend angle depends greatly on the uniformity of the work metal thickness.

Acute angles are formed by the die and punch (Fig. 22d). The air-bending technique, which used a die deep enough so the workpiece does not bottom out on the die, is often used to produce acute angles.

Flattening dies, shown in Fig. 22(e), are used to produce three types of hems after the metal has been formed into an acute angle. A combination die produces an acute angle on one workpiece and a hem on another, so that a piece is started and a piece completed with each stroke of the press brake.

Gooseneck punches (Fig. 22g) and narrow-body or special clearance punches (Fig. 22h) are used to form workpieces to shapes that prevent the use of punches having conventional width.

Selection of Tool Material

Selection of tool material for punches and dies used in press brakes depends on the composition of the work metal, the shape of the workpiece (severity of forming), and the quantity to be produced. The tool material used for press-brake bending and forming ranges from hardwood to cemented carbide, although the use of carbide has usually been confined to inserts at high-wear areas. Hardwood and carbide represent the rare extremes; hardwood is suitable only for making a few simple bends in the most formable work metal, and cemented carbide would be considered only for making severe bends in a less-formable work metal (such as high-strength low-alloy steel) in high production. Most dies and punches used for simple V-bending operations are made from low-carbon steel (such as 1020) or gray iron. Both of these materials are inexpensive and give acceptable tool life in mild service.

Press Forming of Low-Carbon Steel

PRESS FORMING shapes the workpiece with a punch and die. The applied forces may be tensile, compressive, bending, shearing, or various combinations of these. In some applications, the metal requires appreciable stretching in order to retain the shape of the formed part.

Presses

Restriking, coining, and embossing are usually done in presses with more available force capacity than that needed for simple forming of similarly sized areas, because in these operations the metal is confined while being forced into plastic flow. Progressive dies are used in presses with enough force capacity to meet the total demands of the various stations.

Transfer Presses. In transfer machines (eyelet machines), the mechanism for moving the workpiece from station to station is a part of the machine to which suitable transfer fingers are attached. Transfer presses are generally long-bed straight-side presses. The transfer mechanism as a part of the press is actuated by the main press drive or is powered separately. A dial feed is a transfer mechanism that moves the workpiece from die to die in a circular path rather than in a straight line. Transfer press technology has progressed to the point at which large automotive outer body panels can be formed in transfer presses.

Multiple-slide machines are designed for automatic, complete production of a variety of small formed parts. In these units flat stock is fed into a straightener and then a feed mechanism. It then progresses through one or more presses incorporated in the multiple-slide machine for operations such as piercing, notching, and bending--often in a progressive die. The feed mechanism then moves the metal into the multiple-slide forming area, where it is first severed by a cutoff mechanism to predetermined lengths. The piece is usually formed around a center post by four sets of tools mounted 90° apart around the forming post. Finally, the part is stripped off the center post and dropped through a hole in the bed.

Speed of Forming

Speed of forming has little effect on the formability of steels used for simple bending or flanging or for moderate stretching. The maximum velocity of the punch when it contacts the blank in conventional press forming is usually not greater than about 1 m/s (200 ft/min). However, the steels used for most parts that involve local stretching of more than

20% in forming move considerably over the face of the punch or flow appreciably over the blankholder. The flow of the metal in such operations is controlled by frictional forces so sensitive to speed that the steel often stretches to failure before moving against the frictional forces, provided the punch velocity exceeds a critical value, which differs for each steel and die combination. A maximum punch velocity of 0.2 m/s (40 ft/min) is recommended; high punch speeds also shorten tool life.

Lubrication

The lubricant used usually has little effect on the grade of steel selected to form a given part. The main purposes of a lubricant are to prevent die galling and die wear and to reduce the friction over critical areas, thus allowing proper flow of metal and possibly a reduction in severity class. The selection of the optimal lubricant for a given part is complex and depends on part geometry and the forming process used.

In progressive dies, a light oil sprayed on the strip as it enters the die is often enough to keep the stock lubricated through all stages. The oil is generally applied to the stock between the feeding device and the die.

Dies

Dies for press forming low-carbon steel are made from a wide range of materials, including plastics, cast irons, tool steels, and cemented carbides. Severity of forming, number of parts to be produced, workpiece shape, work metal hardness, specified surface condition, and tolerances affect selection of the die material.

Low-carbon steel can be formed by any of the several types of dies described in this section. Workpiece size and shape, production volume, tolerances, and available presses are the major factors that determine the most suitable type of die for a specific application.

Single-operation dies perform one operation at a time and are individually loaded and unloaded. They are usually set up in a press, and the operation is performed on a specific lot size. The die is then removed from the press, and the next die in the sequence is set up. For continuous production, a line of presses--each operating a single die--can produce finished pieces from raw stock without interruption for change in setup. Occasionally, more than one die is set up in a press at a time, and the parts are moved manually from one die to the next.

Compound dies are one-station dies in which more than one operation is done on a workpiece in one press stroke without relocating the workpiece in the die. The operations must be such that they do not weaken the die elements or restrict other operations. The operations generally are successive in the course of the press stroke, rather than simultaneous. Typical combinations of operations include: cutting a blank from a strip and then forming, lancing and forming a tab or louver, and forming a flange and embossing a stiffening bead.

When a die is used for blanking and forming a part, holes often can be pierced in the bottom with the same die. When pierced holes are required in a flange, piercing should be done after the flange has been formed; otherwise, the hole (and perhaps the edge of the flange) can distort. The combination of lancing and forming is common. Continued travel of the lancing punch does the forming. Flanging can be combined with forming or embossing if no metal flow is necessary after the flange has been formed.

Several operations can be performed successively on a workpiece in a press using two or more compound or single-operation dies. The parts can be transferred manually from die to die, eliminating storage and transfer between presses. High-capacity, large-bed press can be used most efficiently for several operations during each press stroke.

Progressive dies contain two or more cavities, or die stations. One or more operations are done on the workpiece at each die station. As the outline of the workpiece is developed in the trimming or forming stations, connecting tabs link the workpiece to the strip until the workpiece reaches the last station, where it is cut off and ejected from the die. Pilot holes that are engaged by pilot pins in the die keep the workpieces aligned and properly spaced as they progress through the die.

Although a progressive die runs more slowly than a single-operation die or a compound die for similar work, overall production is usually higher because the die is operated more continuously. Dies are used to perform an almost endless variety of operations on one piece. Operations that can be combined in a progressive die include notching, piercing, coining, embossing, lancing, forming, cupping, drawing, and trimming.

Transfer dies are similar to progressive dies except that the workpieces are not attached to a strip but are mechanically moved from station to station. A blank is automatically fed into the first station and moved to the next at each press stroke. The first station can be a blanking die, which cuts a blank from manually or automatically fed stock during each press stroke.

Press Forming of High-Carbon Steel

HIGH-CARBON STEEL strip (including spring steel and tool steel) is blanked, pierced, and formed to make a variety of parts. The practices, precautions, presses, and tools used in making high-carbon steel parts are comparable to those used for producing similar parts of low-carbon steel. There are differences, however: more force is required for high-carbon steel because of its higher strength; greater clearance between the punch and die is necessary in blanking and piercing; and more wear-resistant tool material may be required before acceptable tool life can be obtained.

Blanking and Piercing

The most important difference between the blanking and piercing of high-carbon and of low-carbon steel is that greater clearance between punch and die is required for high-carbon steels. Although the complexity of the workpiece and the total quantity to be blanked are more significant factors than work metal composition in the selection of tool material, the hardness of the work metal is nevertheless significant. Carbide dies are often used for large quantities. Die life in blanking and piercing of high-carbon steel varies with different applications, depending greatly on the dimensional accuracy that must be maintained and the burr height that can be tolerated on the blanked parts.

Forming Pretempered Steel

Mild forming of high-carbon steel in the quenched-and-tempered (pretempered) condition (usually 47 to 55 HRC) is common practice. The severity of forming that can be done without cracking of the work metal depends mainly on thickness. When metal is no more than about 0.38 mm (0.015 in.) thick, relatively severe bends without fracturing the work metal are possible. However, as metal thickness increases, the amount of forming of pretempered steel decreases rapidly.

Forming Annealed Steel

Moderately severe forming is possible with cold-rolled stock that has not been quenched and tempered and on high-carbon steel that has been spheroidize-annealed. These materials usually are hardened and tempered after forming to improve spring properties. Table 6 shows the effect of carbon content of steel on bendability and demonstrates the major importance of sheet thickness.

Table 6 Typical effects of carbon content and sheet thickness on minimum bend radius of annealed steels

Thickness of sheet		Minimum bend radius					
		Steels 1020 to 1025		**Steels 4130 and 8630**		**Steels 1070 and 1095**	
mm	**in.**	**mm**	**in.**	**mm**	**in.**	**mm**	**in.**
0.41	0.016	0.8	0.03	0.8	0.03	1.5	0.06
0.51	0.020	0.8	0.03	0.8	0.03	1.5	0.06
0.64	0.025	0.8	0.03	0.8	0.03	1.5	0.06
0.76	0.030	0.8	0.03	1.5	0.06	2.3	0.09
0.89	0.035	1.5	0.06	1.5	0.06	2.3	0.09
1.07	0.042	1.5	0.06	1.5	0.06	3.3	0.13
1.27	0.050	1.5	0.06	2.3	0.09	3.3	0.13
1.57	0.062	1.5	0.06	2.3	0.09	4.1	0.16
1.98	0.078	2.3	0.09	3.3	0.13	4.8	0.19
2.36	0.093	2.3	0.09	4.1	0.16	6.4	0.25
2.77	0.109	3.3	0.13	4.1	0.16	7.9	0.31
3.18	0.125	3.3	0.13	4.8	0.19	7.9	0.31

4.75	0.187	4.8	0.19	7.9	0.31	12.7	0.50

Press Forming of Coated Steel

COATED STEEL sheet or strip is formed in the same presses as those used for forming uncoated steel. Forming procedures, however, sometimes must be modified, depending on the type of coating. During processing, scratching or breaking of the coating (sometimes only marring of the surface) must be avoided because these defects could cause rejection of the finished part.

Effect of Coating Process on Substrate Formability

Coated steels can be categorized according to the formability of the substrate. However, the method used to apply the coating can affect the metallurgical structure of the substrate and can therefore affect its properties.

The most prevalent coated steel that is currently in use is zinc-coated (galvanized) steel. Steel can be galvanized by hot dipping or electrogalvanizing.

Hot-Dip Galvanizing. Hot-dip galvanized steel is produced by one of two basic processes, depending on the properties required. A low-temperature process (455 to 480 °C, or 850 to 900 °F) is used when the steel is pre-annealed to achieve a soft, ductile structure and good formability. Higher temperatures (675 to 870 °C, or 1250 to 1600 °F) are used for in-line annealing (that is, the steel substrate is annealed as the hot dip coating is applied). Because of the short duration of the in-line annealing process, steels processed by this method are less formable than steels that are coated at lower temperature. Depending on carbon content, steels coated by the high-temperature hot-dip process may require post-annealing to enhance formability. Low-carbon steels often require post-annealing to restore full formability; extra-low-carbon steels (0.01% C) normally do not require post-annealing.

Electrogalvanizing. Coated at temperatures at or near ambient, the properties of electrogalvanized steel sheet are nearly identical to those of uncoated cold-rolled steel.

Galvanized Steels

The formability of galvanized steels is reduced to some extent by the brittle iron-zinc alloy layer that is produced between the metallic zinc and the steel base during hot-dip galvanizing. The thickness of the alloy layer depends on the temperature-time cycle in galvanizing, but it is also affected by the percentage of other metals, especially lead and aluminum, in the molten-zinc bath. The decrease in formability is usually in direct proportion to the thickness of the iron-zinc alloy layer. Modern hot-dip galvanizing processes use special thermal cycles and low-lead low-aluminum coating materials to minimize formation of the iron-zinc alloy layer.

In deep drawing, the beneficial effects of the free-zinc layer on the surface of the work metal outweigh the adverse effect of the alloy layer, often permitting greater reductions and greater draw depths than with similar uncoated steel. The layer of soft metallic zinc prevents galling during forming by eliminating direct contact between the steel substrate and the punch.

Formability is also influenced by other factors; chiefly, the initial properties of the steel base; the amount of mechanical work before or after galvanizing; and the response of the steel to the heating cycle for galvanizing, to supplementary heat treatments, and to aging. These factors often have a greater effect on the formability of galvanized steel than the galvanized coating does.

Tools for forming zinc-coated steel parts are conventional, made of cast iron and standard tool steels. However, parts formed of commercial quality (CQ) continuous-annealed steel or of steel over 1.52 mm (0.060 in.) thick require more compensation for springback than conventional box-annealed steel and uncoated steel, which have lower yield strengths and hardnesses. Post-heat-treated continuous-annealed and box-annealed drawing quality (DQ) galvanized steels require the same tooling as uncoated steels in most forming operations.

Aluminum-Coated Steels

Moderately severe forming is possible with hot-dip aluminum-coated (aluminized) steel. The same dies and pressworking practices used for uncoated steel are applicable to aluminum-coated stock. Drawing compounds are recommended for forming and drawing operations. Requirements for corrosion resistance in service often limit the permissible severity of forming. Hairline cracks that develop in the aluminum coating lead to lower service life at high temperature or in atmospheric exposure.

Tin-Coated and Terne-Coated Steels

The steels to which tin and terne coatings are applied vary in composition for different products and among different manufacturers, but are generally low-carbon grades similar to 1008 or 1010. Nearly all of the common forming methods are used on tin-coated and terne-coated low-carbon steel. Spinning is not ordinarily performed on these materials because of the likelihood of excessively thinning or fusing the coatings. The thickness of tin on electroplated mill products ordinarily ranges from 0.4 to 2.3 μm (15 to 90 μin.) per side. Hot-dip products have coating thicknesses of 1.7 to 3.8 μm (66 to 150 μin.) per side.

The behavior of terneplate in forming is generally the same as that of tin plate. Because of its high lead content, terneplate is toxic and therefore not suitable for food containers, but it is formed into containers for gasoline and paint. Terneplate is used in formed products such as roofing, doorframes, and automotive parts because of its excellent resistance to atmospheric corrosion and its low cost.

Nickel-Plated and Chromium-Plated Steels

Press forming and roll forming are sometimes performed on steel that has been electroplated in the coil with decorative copper-nickel or copper-nickel-chromium. More often, however, parts are formed to final shape before electroplating with these materials.

Conventional lubricants can be used to press form this material, particularly in high-volume production. Sometimes, however, no lubricant is used in making decorative parts. Instead, surface contact between the work metal and tools is prevented by the use of strippable plastic coatings or adhesive-backed paper on the work metal, or of loose paper between the work metal and the punch or the die. These materials protect the decorative finish on the preplated steel, prevent galling, and reduce friction for forming. They can also be removed from the completed parts without harming the finish.

Forming of Steel Strip in Multiple-Slide Machines

MULTIPLE-SLIDE FORMING is a process in which the workpiece is progressively formed in a combination of units that can be used in various ways for the automated fabrication of a large variety of simple and intricately shaped parts from coil stock or wire. Operations such as straightening, feeding, trimming, blanking, embossing, coining, lettering, forming to shape, and ejecting can all be done in one cycle of a multiple-slide machine. Forming is generally limited to bending operations, but the four slides and center post permit the fabrication of very complex parts. Deep drawing is generally not done in the forming or press stations of a multiple-slide machine.

Applicability

Multiple-slide forming is used to produce shapes from coiled strip or wire. The maximum size of workpiece that can be formed from strip metal in a multiple-slide machine is 203 mm (8 in.) wide by 685 mm (27 in.) long. Parts made from wire up to 1015 mm (40 in.) long (or longer if a special machine is used) and up to 9.5 mm ($\frac{3}{8}$ in.) in diameter can be formed automatically from coil stock.

If the work metal is comparatively thin and the bending is not severe, tempered strip material can be formed. Plated or coated materials can be formed, but it is usually better to coat after forming because it is difficult to avoid marring coated surfaces during forming. However, nonmetallic inserts at appropriate points in the straightener, feeder, and forming tools can be used to reduce tool marks.

Springback must be considered in bending materials such as stainless steel, phosphor bronze, certain grades of brass and beryllium copper, or high-carbon steel. Adjustments can be made in the forming tools to provide the amount of overbending required for the accuracy of the finished work.

More than one piece can be made in each cycle of a multiple-slide machine. For example, a part that had been made in seven conventional press operations was replanned for the multiple-slide production of four pieces per cycle at 200 cycles per minute.

Multiple-Slide Machines

Multiple-slide machines are made in a range of sizes, all similar in construction and principle. The larger machines have a longer die space, which allows more die stations to be used in the manufacture of complicated components. Generally, the number of strokes per minute decreases and the horsepower increases as the machine size increases.

The four forming slides of a typical multiple-slide machine are generally sufficient for ordinary part-forming needs. However, complex parts can be formed at two or three levels around the center post, thus doubling or tripling the number of forming positions available.

Figure 23 shows a plan view of the main units of a medium-size multiple-slide machine. In a typical machine, four shafts (A, B, C, and D) mounted to a flat-top bed plate are driven at equal speed through spur gearing (E) by an electric motor. Each of the four shafts is fitted with a positive-action cam (F) that drives a slide (G) on which the forming tools can be secured. In the center of the machine is a vertical post (H) into which the center post or former is fixed and around which the work material is bent. The formed workpiece is removed from the center post by a stripper mechanism, which usually consists of a hardened steel plate surrounding the center post and secured to a vertical rod operated by a cam (F) on the right-hand shaft to give up-and-down motion to the stripper.

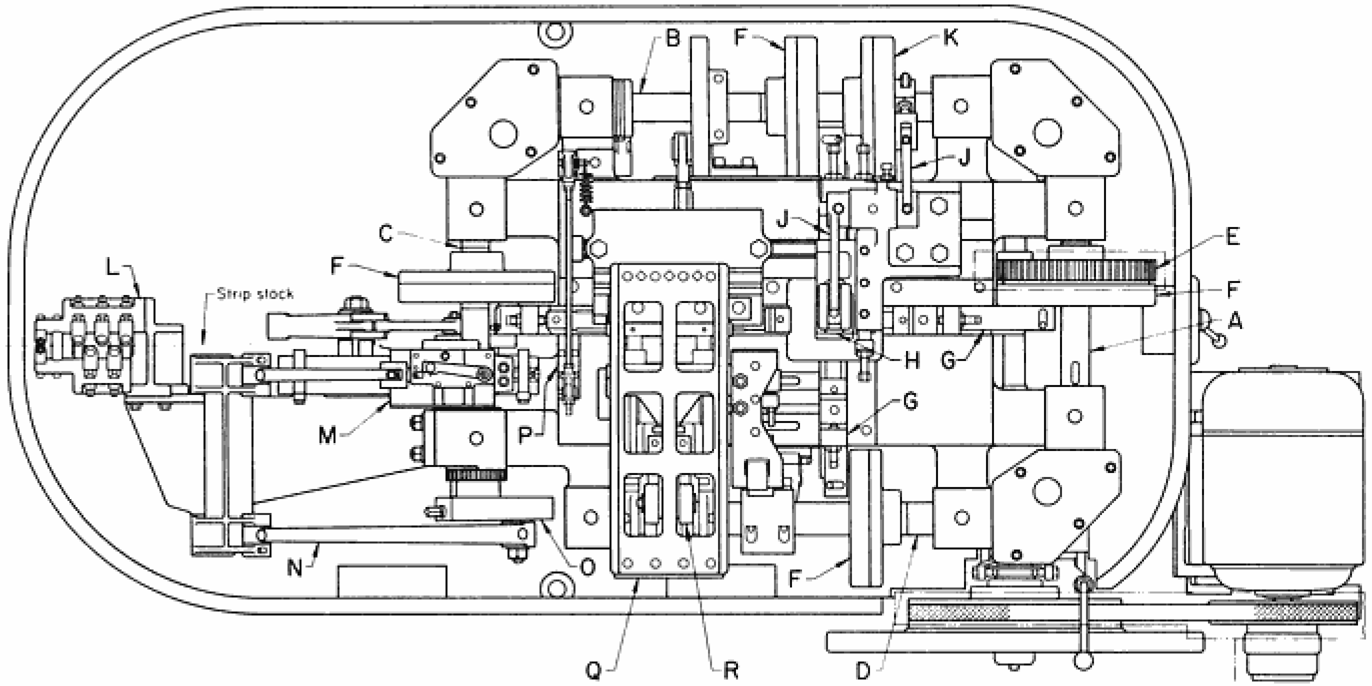


Fig. 23 Plan view of a multiple-slide machine showing major components. A to D, integrated shafts; E, spur gearing; F, positive-action cam; G, slide; H, vertical post; J, bell crank; K and R, cams; L, stock straightener; M, automatic gripper in feed slide; N, links; O, adjustable crank; P, stationary gripper with cam-operated jaws; Q, horizontal press with dies; R, cam. See text for description of operation.

To the left side of the machine proper is a stock straightener (L), shown in working position with strip stock passing through it. Intermittent feeding of the work metal is accomplished by an automatic gripper in the feed slide (M) and an adjustable crank (O), which is attached to a shaft (C). A separate gripper (P) is provided with cam-operated jaws, which grip the strip on the return stroke of the feed slide to prevent backward motion of the strip.

The work metal strip, fed through the machine in a vertical plane (on edge), passes horizontally through dies in a horizontal press (Q). A short, powerful stroke is given to the horizontal press slide by a cam on the front shaft (D) (see Fig. 23).

Deep Drawing

DRAWING is a process in which sheet metal is formed into round or square cup-shape parts. The work metal is placed over a shaped die and pressed into the die with a punch (Fig. 24). The term deep drawing implies that some drawing-in of the flange metal occurs and that the formed parts are deeper than those that could be obtained by simply stretching the metal over a die. Clearance between the male punch and the female die is closely controlled to minimize the free span so that there is no wrinkling of the sidewall. This clearance is sufficient to prevent ironing of the metal being drawn into the sidewall in the deep-drawing process. If ironing of the walls is to be part of the process, it is done in operations subsequent to deep drawing.

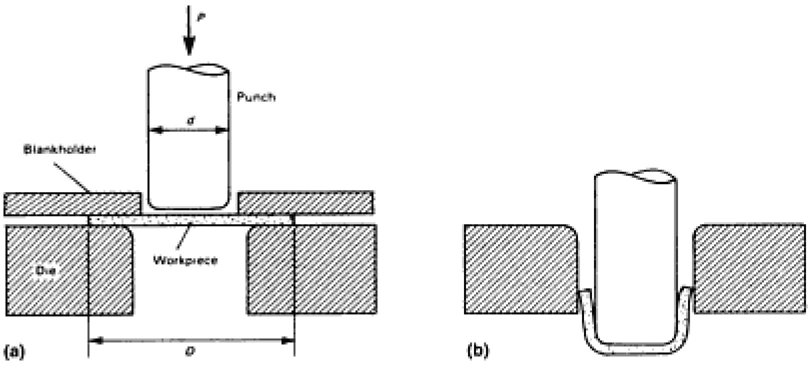


Fig. 24 Deep drawing of a cylindrical cup. (a) Before drawing. (b) After drawing.

Suitable radii in the punch bottom to side edge, as well as the approach to the die opening, are necessary to allow the metal sheet to be formed without tearing. In most deep-drawing operations, the part has a solid bottom to form a container and a retained flange that is trimmed later in the processing. In some cases, the cup shape is fully drawn into the female die cavity, and a straight-wall cup shape is ejected through the die opening. To control the flange area and to prevent wrinkling, a hold-down force is applied to the blank to keep it in contact with the upper surface of the die. A suitable subpress or a double-action press is required. Presses can be either hydraulic or mechanical devices, but hydraulic presses are preferred because of better control of the rate of punch travel.

Fundamentals of Drawing

A flat blank is formed into a cup by forcing a punch against the center portion of a blank that rests on the die ring. The progressive stages of metal flow in drawing a cup from a flat blank are shown schematically in Fig. 25. During the first stage, the punch contacts the blank (Fig. 25a), and metal section 1 is bent and wrapped around the punch nose (Fig. 25b). Simultaneously and in sequence, the outer sections of the blank (2 and 3 in Fig. 25) move radially toward the center of the blank until the remainder of the blank has bent around the punch nose and a straight-wall cup is formed (Fig. 25c and d). During drawing, the center of the blank (punch area, Fig. 25a) is essentially unchanged as it forms the bottom of the drawn cup. The areas that become the sidewall of the cup (1, 2, and 3, Fig. 25) change from the shape of annular segments to longer parallel-side cylindrical elements as they are drawn over the die radius. Metal can flow until all the metal has been drawn over the die radius, or a flange can be retained.

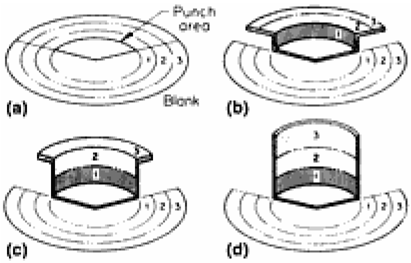


Fig. 25 Progression of metal flow in drawing a cup from a flat blank

A blankholder is used in a draw die to prevent the formation of wrinkles as compressive action rearranges the metal from flange to sidewall. Wrinkling starts because of some lack of uniformity in the movement or because of the resistance to movement in the cross section of the metal.

Drawability

The drawability of a metal depends on two factors: the ability of the material in the flange region to flow easily in the plane of the sheet under shear, and the ability of the sidewall material to resist deformation in the thickness direction. Taking both of these factors into account, it is desirable in drawing operations to maximize material flow in the plane of the sheet and to maximize resistance to materials flow in a direction perpendicular to the plane of the sheet. Low flow strength in the plane of the sheet is of little value if the work material also has low flow strength in the thickness direction.

The flow strength of sheet metal in the thickness direction is difficult to measure, but the plastic strain ratio *r* compares strengths in the plane and thickness direction by determining true strains in these directions in a tension test. A high *r* value is the measure of a material with good deep-drawing characteristics. Table 7 lists *r* values for carbon steel sheet in various conditions. Equations for determining the plastic strain ratio can be found in the Section "Design Considerations and Materials Selection" in this Handbook (see the discussion of formability in the article "Factors in Materials Selection").

Table 7 Typical mechanical properties of low-carbon sheet steels

Quality level	Tensile strength		Yield strength		Elongation, % in 50 mm (2 in.)	Plastic-strain ratio, *r*	Strain-hardening exponent, *n*	Hardness, HRB
	MPa	**ksi**	**MPa**	**ksi**				
Hot rolled								
Commercial quality	358	52	234	34	35	1.0	0.18	58
Drawing quality	345	50	220	32	39	1.0	0.19	52
Drawing quality, aluminum killed	358	52	234	34	38	1.0	0.19	54
Cold rolled, box annealed								
Commercial quality	331	48	234	34	36	1.2	0.20	50
Drawing quality	317	46	207	30	40	1.2	0.21	42
Drawing quality, aluminum killed	303	44	193	28	42	1.5	0.22	42

Drawability can also be expressed in terms of a limiting draw ratio or percentage of reduction based on results of Swift cup testing. The limiting draw ratio is the ratio of the diameter *D* of the largest blank that can be successfully drawn to the diameter of the punch *d*:

$$\mathrm{LDR} = \frac{D}{d}$$

Percentage of reduction would then be defined as:

$$\text{Percentage of reduction} = \frac{100\,(D - d)}{D}$$

Additional information on formability testing can be found in the Section "Mechanical, Wear, and Corrosion Testing" in this Handbook.

Earing in deep-drawn parts is related to planar anisotropy. The sheet metal therefore may be stronger in one direction than in other directions in the plane of the sheet. This causes ears to form on the drawn part even when a circular blank is used. In practice, enough extra metal is left on the drawn cup so that the ears can be trimmed.

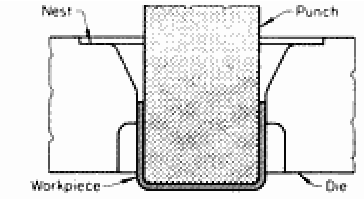
Presses

Sheet metal is drawn in either hydraulic or mechanical presses. Double-action presses are required for most deep drawing because a more uniform blank holding force can be maintained for the entire stroke than is possible with a spring-loaded blankholder. Double-action hydraulic presses with a die cushion are often preferred for deep drawing because of their constant drawing speed, stroke adjustment, and uniformity of clamping pressure. Regardless of the source of power for the slides, double-action straight-side presses with die cushions are best for deep drawing. Straight-side presses provide a wide choice of tonnage capacity, bed size, stroke, and shut height.

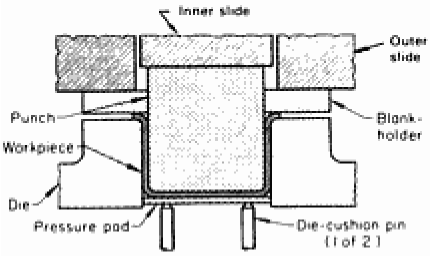
Drawing force requirements, die space, and length of stroke are the most important considerations in selecting a press for deep drawing. The condition of the crankshaft, connection bearings, and gibs is also a factor in press selection.

Dies

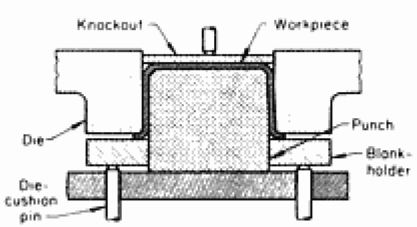
Single-action dies (Fig. 26a) are the simplest of all drawing dies and have only a punch and a die. A nest or locator is provided to position the blank. The drawn part is pushed through the die and stripped from the punch by the counterbore in the bottom of the die. The rim of the cup expands slightly to make this possible. Single-action dies can be used only when the forming limit permits cupping without the use of a blankholder.



(a) Single-action die



(b) Double-action die



(c) Double-action die, inverted type

Fig. 26 Components of three types of simple dies shown in a setup used for drawing a round cup. See text for

discussion.

Double-action dies have a blankholder, permitting greater reductions and the drawing of flanged parts (Fig. 26b). In this design, the die is mounted on the lower shoe; the punch is attached to the inner, or punch slide; and the blankholder is attached to the outer slide. The pressure pad is used to hold the blank firmly against the punch nose during the drawing operation and to lift the drawn cup from the die. If a die cushion is not available, springs or air or hydraulic cylinders can be used; however, they are less effective than a die cushion, especially for deep draws.

An inverted double-action die (Fig. 26c) is used in single-action presses. In this design, the punch is mounted on the lower shoe, the die on the upper shoe. A die cushion can supply the blank-holding force, or springs or air or hydraulic cylinders are incorporated into the die to supply the necessary blank-holding force. The drawn cup is removed from the die on the upstroke of the ram when the pin-like extension of the knockout strikes a stationary knockout bar attached to the press frame.

Compound Dies. When the initial cost is warranted by production demands, it is practical to combine several operations in a single die. Blanking and drawing operations are commonly placed in compound dies. With compound dies, workpieces can be produced several times as fast as by the simple dies.

Progressive Dies. The initial cost and length of bed needed for progressive dies usually limit their application to relatively small workpieces.

Multiple Dies. In conjunction with transfer mechanisms, multiple dies are often used instead of progressive dies for mass producing larger parts. Multiple dies and transfer mechanisms are practical for a wider range of workpiece sizes than progressive dies are.

Die and Punch Materials

The material used for dies and punches for drawing sheet metal depends on work metal composition, workpiece size, severity of the draw, quantity of parts to be drawn, and tolerances and surface finish specified for the drawn workpieces. To meet the wide range of requirements, punch and die materials include polyester, epoxy, phenolic, or nylon resins; highly alloyed tool steels with nitrided surfaces; and cemented carbides.

Lubrication

Lubricants are used in most drawing operations. They range from ordinary machine oil to pigmented compounds. Selection of lubricant is primarily based on the ability to prevent galling, wrinkling, or tearing during deep drawing. It is also influenced by ease of application and removal, corrosivity, and other factors.

Lubricants used in drawing steel (Table 8) are selected according to severity of draw or the percentage of reduction from blank to cup diameter. Zinc phosphate conversion coating of the steel to be drawn is helpful for any drawing operation, and the importance of phosphate coating increases as the severity of the draw increases.

Table 8 Lubricants commonly used for the drawing of low-carbon steel

Type or composition of lubricant	Ease of removal by:		Protection against rusting
	Water-base cleaners	**Degreasers or solvents**	
Water-base lubricants			
Low severity (10% or less)			
Water emulsion of 5-20% general-purpose soluble oil or wax	Very good	Good	Fair
Moderate severity (11-20%)			
Water solution of 5-20% soap	Very good	Very poor	Fair
Water emulsion of heavy-duty soluble oil (contains sulfurized or chlorinated additives)	Very good	Good	Fair
High severity (21-40%)			
Soap-fat paste, diluted with water (may contain wax)	Fair	Poor	Fair
Water emulsion of heavy-duty soluble oil (contains a high concentration of sulfurized or chlorinated additives)	Very good	Good	Fair to poor
Maximum severity (>40%)			
Pigmented soap-fat paste, diluted with water	Poor	Very poor	Good
Dry soap or wax (applied from water solution or dispersion); may contain soluble filler such as borax	Good	Very poor	Good
Oil-base lubricants			
Low severity (10% or less)			
Mill oil, residual	Good	Very good	Fair
Mineral oil	Good	Very good	Fair
Vanishing oil	Removal not required		. . .
Moderate severity (11-20%)			
Mineral oil plus 10-30% fatty oil	Good	Very good	Fair
Mineral oil plus 2-20% sulfurized or chlorinated oil (extreme-pressure oil)	Good to fair	Good	Fair to poor
High severity (21-40%)			
Fatty oil	Fair	Fair	Fair
Mineral oil plus 5-50% of:			
Nonemulsifiable chlorinated oil	Poor	Good	Very poor
Emulsifiable chlorinated oil	Good	Good	Very poor
Concentrated phosphated oil	Fair	Fair	Fair
Maximum severity (>40%)			
Blend of pigmented soap-fat paste with mineral oil	Poor	Poor	Fair
Concentrated sulfochlorinated oil (may contain some fatty oil):			
Nonemulsifiable	Very poor	Fair	Poor
Emulsifiable	Good	Fair	Poor
Concentrated chlorinated oil:			
Nonemulsifiable	Very poor	Fair	Very poor
Emulsifiable	Good	Fair	Very poor

Severity is indicated by the percentage of reduction in diameter in drawing a cylindrical shell.

Direct Redrawing

In direct redrawing in a single-action die, the drawn cup is slipped over the punch and is loaded in the die (Fig. 27). At first, the bottom of the cup is wrapped around the punch nose without reducing the diameter of the cylindrical section. The sidewall section then enters the die and is gradually reduced to its final diameter. Metal flow takes place as the cup is drawn into the die so that the wall of the redrawn shell is parallel to, and deeper than, the wall of the cup at the start of the redraw. At the beginning of redrawing, the cup must be supported and guided by a recess in the die or by a blankholder to prevent it from tipping, which would result in an uneven shell.

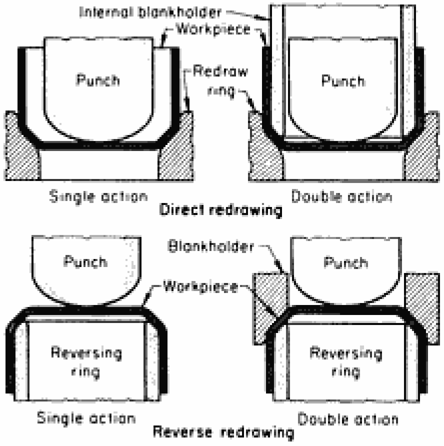


Fig. 27 Direct and reverse redrawing in single-action and double-action dies

In a single-action redraw, the metal must be thick enough to withstand the compressive forces set up in reducing the cup diameter without wrinkling. Wrinkling can be prevented by the use of an internal blankholder and a double-action press, which usually permits a shell to be formed in fewer operations than by single-action drawing without the use of a blankholder.

Reverse Redrawing

In reverse redrawing, the cupped workpiece is placed over a reversing ring and redrawn in the direction opposite to that used for drawing the initial cup. Reverse redrawing can be done with or without a blankholder (Fig. 27). The blankholder serves the same purposes as in direct redrawing. Reverse redrawing can be performed in a progressive die as well as in single-stage dies if the operations are divided to distribute the work and to reduce the severity of each stage.

Advantages of reverse drawing as compared with direct redrawing include:

- Metal can be drawn and redrawn in one stroke of a triple-action hydraulic press, or of a double-action mechanical press with a die cushion, which can eliminate the need for a second press.
- Greater reductions per redraw are possible with reverse redrawing.
- One or more intermediate annealing operations can often be eliminated by using the reverse technique.
- Better distribution of metal can be obtained in a complex shape.

In borderline applications, annealing is required between redraws in direct redrawing, but is not needed in reverse redrawing.

The disadvantages or reverse drawing are:

- The technique is not practical for work metal thicker than 6.4 mm ($\frac{1}{4}$ in.).
- Reverse redrawing requires a longer stroke than direct redrawing.

Usually, metals that can be direct redrawn can be reverse redrawn. All of the carbon and low-alloy steels, austenitic and ferritic stainless steels, aluminum alloys, and copper alloys can be reverse redrawn.

Reverse redrawing requires more closely controlled processing than direct redrawing. The blanks should be free from nicks and scratches, especially at the edges.

The restraint in reverse redrawing must be uniform and low. For low friction, polished dies and effective lubrication of the work are needed. Friction also is affected by hold-down pressure and by the shape of the reversing ring. Radii of tools should be as large as practical--ten times the thickness of the work metal if possible.

Stretch Forming

STRETCH FORMING involves forming sheet, bars, and rolled or extruded sections over a form block of the required shape while the workpiece is held in tension. The work metal is often stretched just beyond its yield point (generally 2 to 4% total elongation) to retain permanently the contour of the form block.

The four methods of stretch forming are: stretch draw forming (Fig. 28a and b); stretch wrapping, also called rotary stretch forming (Fig. 28c); compression forming (Fig. 28d); and radial draw forming (Fig. 28e).

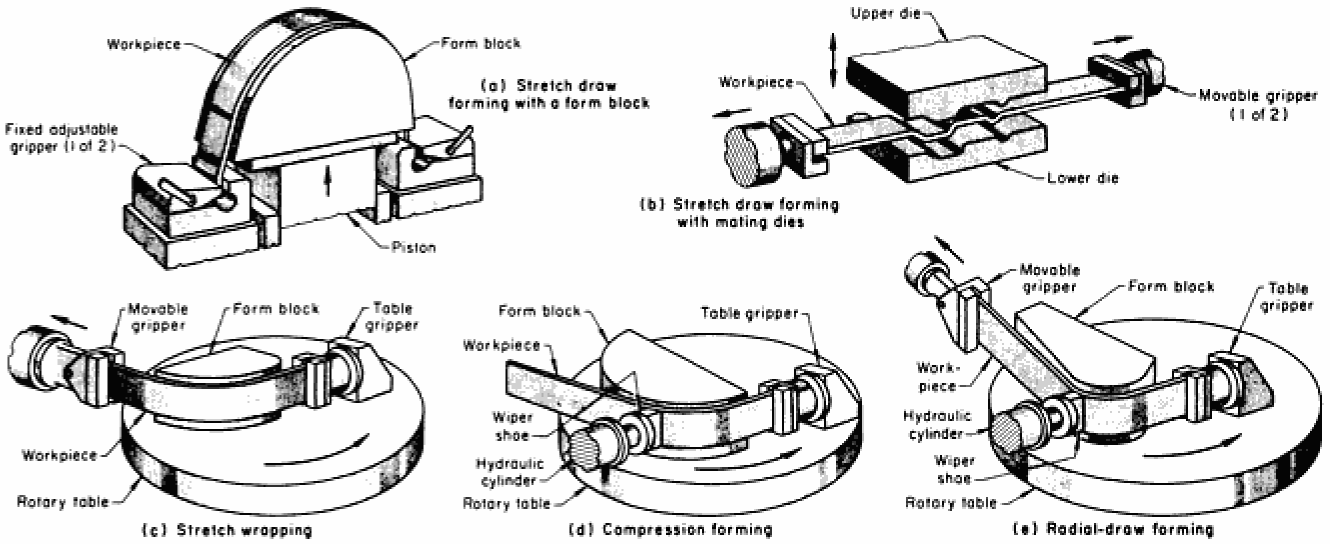

Workpiece
Form block
(a) Stretch draw forming with a form block
Fixed adjustable gripper (1 of 2)
Piston
Upper die
Workpiece
Movable gripper (1 of 2)
Lower die
(b) Stretch draw forming with mating dies
Movable gripper
Form block
Table gripper
Workpiece
Rotary table
(c) Stretch wrapping
Form block
Table gripper
Workpiece
Wiper shoe
Hydraulic cylinder
Rotary table
(d) Compression forming
Movable gripper
Form block
Table gripper
Work-piece
Hydraulic cylinder
Wiper shoe
Rotary table
(e) Radial-draw forming

Fig. 28 Fundamentals of the techniques involved in the four methods of stretch forming

Applicability

Almost any shape that can be produced by other sheet-forming methods can be produced by stretch forming. Drawn shapes that involve metal flow, particularly straight cylindrical shells, and details that result from compression operations such as coining and embossing, cannot be made. However, some embossing is done by the mating-die method of stretch draw forming.

Stretch forming is used to form aerospace parts from steel, nickel, aluminum, and titanium alloys and other heat-resistant and refractory metals. Some of these parts are difficult or impossible to form by other methods.

Stretch forming is also used to shape automotive body panels, both inner and outer, and frame members that could be formed by other processes but at higher cost. Architectural shapes and aerospace forms that call for compound curves, reverse bends, twists, and bends in two or more planes are also produced by stretch forming.

Machines and Accessories

Stretch wrapping, compression forming, and radial-draw forming use rotary tables on which are mounted the form block, a ram gripping and tensioning or wiping device, and a mechanically or hydraulically actuated table gripper (Fig. 28c-e). In stretch wrapping, the workpiece is pulled from one end, wrapping the metal around the form block. In compression forming, a wiper shoe presses the workpiece against the form block. Radial-draw forming combines both pulling and pressing of the metal. Machines used for these operations have capacities to 8900 kN (1000 tonf).

Stretch draw forming is done in three types of machines. In one type, the form block is mounted on a hydraulic cylinder and is pushed into the blank, which is held in tension by a pair of pivoting grippers. In another type, the form block is fixed to the table and a pair of grippers actuated by slides or a hydraulic cylinder draws the blank around it. The third type of machine is a single-action hydraulic press equipped with a two-piece mating die. Grippers pull the blank over the lower die, then the upper die descends to produce the workpiece (Fig. 28b). The hydraulic presses ordinarily used in stretch draw forming have capacities of 1800 to 7100 kN (200 to 800 tonf).

Accessory Equipment. Grippers and wiping shoes or rollers are made to conform to the rolled or extruded shape that is to be stretch formed. Jaws used for gripping sheet in stretch draw forming can be segmented or contoured to apply equal stretch to all parts of the sheet as it is formed.

Spinning

SPINNING forms sheet metal or tubing into seamless hollow cylinders, cones, hemispheres, or other circular shapes by a combination of rotation and force. (Tube spinning is discussed in the following article "Forming of Bars, Tubes, and Wire.") The technique falls into two categories: manual spinning and power spinning.

Any metal that can be cold formed by other methods can be spun. Most spinning takes place without heating the workpiece; sometimes the metal is preheated to increase ductility or to allow thicker sections to be spun.

Manual Spinning

Manual spinning involves no appreciable thinning of the work metal. The operation requires a lathe and it consists of pressing a tool against a circular metal blank that is rotated by the headstock. The blank is usually forced over a mandrel of a predetermined shape, but simple shapes can be spun without a mandrel. Various mechanical devices are used to increase the force that can be applied to the workpiece.

Manual spinning is used to form flanges, rolled rims, cups, cones, and double-curved surfaces of revolution (such as bells). Products include light reflectors, tank ends, covers, housings, shields, components for musical instruments, and aircraft and aerospace components (often with mechanical assistance for increased force).

The practical maximum thickness of low-carbon steel that can be spun without mechanical assistance is 3.2 mm ($\frac{1}{8}$ in.). At this thickness, the diameter can be as great as 1.8 m (72 in.). Diameters can be greater when the sheet steel is thinner, but the maximum practical diameter is often limited by the availability of equipment. The upper limit of thickness increases as work metal ductility increases or as strength decreases. For example, the manual spinning of aluminum as thick as 6.4 mm ($\frac{1}{4}$ in.) is feasible

Equipment for Manual Spinning

A typical tool and workpiece setup for manual spinning is shown in Fig. 29(a). A mandrel is mounted on the headstock of a lathe. A circular blank (workpiece) is clamped to the mandrel by a follower block attached to the tailstock of the lathe. The blank is rotated by the headstock, while a friction-type spinning tool is manually pressed against the blank, forcing the blank over the preshaped mandrel. The tool is mounted on a tool rest by a support pin (fulcrum). The operator presses the tool against the blank by pivoting it around the support pin. The tool rest permits the tool to be moved to different positions.

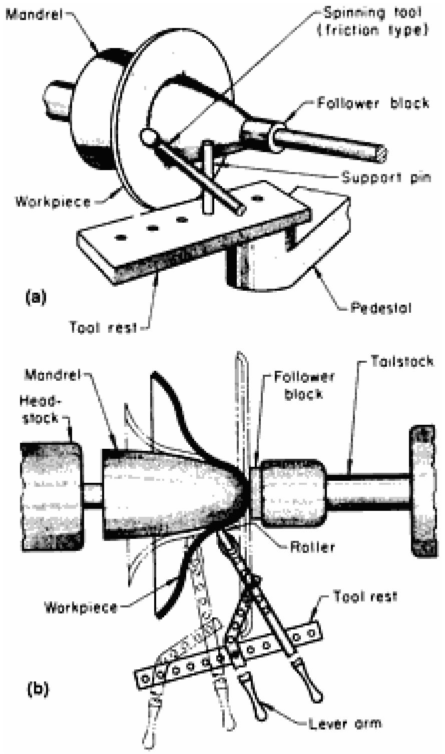


Fig. 29 Manual spinning in a lathe. (a) Setup using a simple hand tool, applied like a pry bar. (b) Setup using scissorlike levers and a roller spinning tool

Figure 29(b) shows a more complex setup for manual spinning. Here, the spinning tools are rollers which are mounted in the fork sections of long levers. The roller is pressed against the workpiece by manipulating the scissor-like levers.

Power Spinning

Power spinning is also known as shear spinning, because in this method metal is intentionally thinned by shear forces as high as 3.5 MN (400 tonf). Power spinning is used in two broad areas of application: cone spinning and tube spinning. Virtually all ductile metals can be processed by power spinning. Products range from small hardware items made in large quantities (metal tumblers, for example) to large components for aerospace applications in unit or low-volume production.

Blanks as large as 6 m (240 in.) in diameter have been successfully power spun. Plate stock up to 25 mm (1 in.) thick can be power spun without heat. When heated, blanks as thick as 140 mm ($5\frac{1}{2}$ in.) can be spun. Conical and curvilinear shapes are most commonly produced from flat (or preformed) blanks by power spinning.

Machines for Power Spinning

Most power spinning requires machines specially built for the purpose. The primary components of such a machine are shown in Fig. 30. Power spinning machines are usually described by capacity: the diameter and length (in inches) of the largest workpiece that can be spun and the amount of force that can be applied to the work. It is also common practice to specify that the machine can spin a given thickness of metal at a 50% reduction in thickness in one pass.

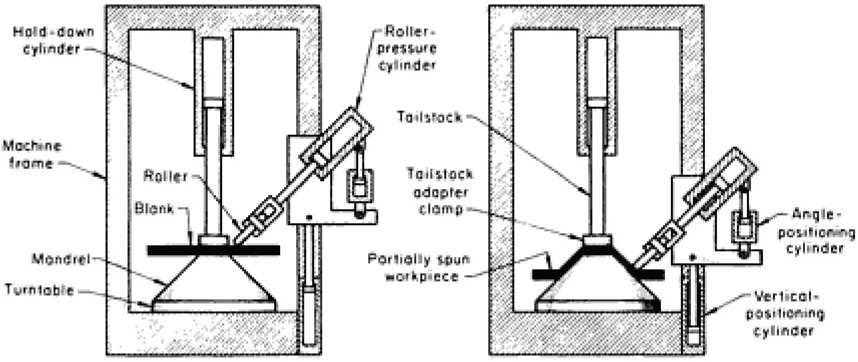


Fig. 30 Schematic illustration of power spinning in a vertical machine

The capacity of spinning machines, which may be horizontal or vertical, ranges from 455 × 380 mm (18 × 15 in.) at 18 kN (4000 lbf) to machines capable of spinning workpieces as large as 6 m (240 in.) in diameter × 6 m (240 in.) long. Force on the work can be as great as 3.5 MN (400 tonf). Machines have been built that spin steel 140 mm (5$\frac{1}{2}$ in.) thick.

Machines for power spinning can be automated to various degrees. Automatic spinning machines are available with computer numerical controls (CNC) to automatically perform the spinning operation.

Rubber-Pad Forming

RUBBER-PAD FORMING, also known as flexible-die forming, uses two tool halves: a rubber pad or a flexible diaphragm (or bladder), and one solid tool half to form a part to final shape. The solid tool half usually is similar to the punch in a conventional die, but it can be the die cavity. The rubber acts somewhat like hydraulic fluid in exerting nearly equal pressure on all workpiece surfaces as it is pressed around the form block.

Rubber-pad forming is used on moderately shallow, recessed parts with simple flanges and relatively simple configurations. Form block height is usually less than 100 mm (3.9 in.). The production rates are relatively high, with cycle times averaging 1 min or less.

Flexible-die forming methods fall into three groups: rubber-pad forming, fluid-cell forming, and fluid forming. Specific processes falling into these three categories are described below.

Rubber-Pad Forming

The Guerin process is synonymous with the term rubber-pad forming. Other processes, which are essentially modified/improved version of the Guerin process, include the Marform process, the trapped-rubber process, and the ASEA Quintus rubber-pad process.

Guerin Process

The Guerin process is the oldest and most basic of the production rubber-pad forming processes. Its advantages are simplicity of equipment, adaptation to small-lot production, and ease of changeover.

Some metals that are commonly formed by this process are listed in Table 9. Titanium can be formed only if the workpiece and the form block are both heated. The resulting deterioration of the rubber pad often makes the process too costly compared with forming by conventional dies.

Table 9 Metals commonly formed by the Guerin process

Metal	Maximum thickness(a)	
	mm	**in.**
Mild forming		
Aluminum alloys		
2024-O, 7075-W	4.7	0.187
2024-T4	1.6	0.064
Austenitic stainless steels		
Annealed	1.3	0.050(b)
Quarter hard	0.8	0.032(c)
Titanium alloys	1.0	0.040(d)
Stretch flanging		
Aluminum alloy 2024-T4	1.6	0.064
Austenitic stainless steels		
Annealed	1.3	0.050

(a) Typical; varies with type of equipment and part design.

(b) Up to 2.0 mm (0.078 in.) when compression dams are used.

(c) Only very mild forming.

(d) When heated to 315 °C (600 °F)

Presses. Almost any hydraulic press can be used for the Guerin process. For maximum forming capability, the force capacity of the press and the area of the rubber pad must be suitable for the operation under consideration. The rubber pad is generally about the same size as the press ram, but it can be smaller.

Tools. The principal tools are the rubber pad and the form block, or punch (Fig. 31). The rubber pad is relatively soft (about Durometer A 60 to 75) and usually three times as deep as the part to be formed. The pad can consist of a solid block of rubber, or of laminated slabs cemented together and held in a retainer.

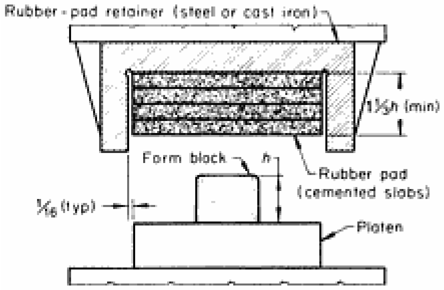

Rubber-pad retainer (steel or cast iron)
1⅓h (min)
Form block
h
Rubber pad (cemented slabs)
1/16 (typ)
Platen

Fig. 31 Tooling and setup for rubber-pad forming by the Guerin process. Dimensions given in inches

Procedure. The rubber-pad retainer is fixed to the upper ram of the press; the platen, containing the form block, is placed on the bed of the press. A blank is placed on the form block and is held in position by two or more locating pins. The pins must be mounted rigidly in the form block so that the rubber will not drive them down into the pinhole or push them out of position. The pins must be no higher than necessary to hold the blank, or they will puncture the rubber pad. In some applications, nests can be used to locate the blank during forming.

As the ram descends, the rubber presses the blank around the form block, thus forming the workpiece. The rubber-pad retainer fits closely around the platen, forming an enclosure that traps the rubber as pressure is applied. The pressure produced in the Guerin process is ordinarily 6.9 to 48 MPa (1 to 7 ksi). The pressure can be increased by reducing the size of the platen. Pressures as high as 140 MPa (20 ksi) have been developed through the use of small platens in high-capacity presses.

Marform Process

This process was developed to apply the inexpensive tooling of the Guerin process to the deep drawing and forming of wrinkle-free shrink flanges. A blankholder plate and a hydraulic cylinder with a pressure-regulating valve are used with a thick rubber pad and a form block similar to those used in the Guerin process. The blank is gripped between the blankholder and the rubber pad. The pressure-regulating valve controls the pressure applied to the blank while it is being drawn over the form block.

For a soft aluminum alloy blank, the diameter can usually be reduced 57%, with reductions as high as 72%. A shell depth equal to the shell diameter is normal when the minimum stock thickness is 1% of the cup diameter. Depths up to three times shell diameter have been reached with multiple-operation forming. The minimum cup diameter is 38 mm ($1\frac{1}{2}$ in.).

Foil as thin as 0.038 mm (0.0015 in.) can be formed by placing the blank between two aluminum blanks about 0.76 mm (0.030 in.) thick and forming the three pieces as a unit. The inner and outer shells are discarded.

Presses. The Marform process is best suited to a single-action hydraulic press in which pressure and speed of operation can be varied and controlled.

Tools. The rubber pad used in Marforming is similar to that used in the Guerin process. It is normally $1\frac{1}{2}$ to 2 times as thick as the total depth of the part, including trim allowance.

Drop Hammer Forming with Trapped Rubber

Similar to the Guerin process for forming shallow workpieces, the trapped-rubber process uses a drop hammer in place of the hydraulic press; the primary differences are faster forming speed and the impact force of the hammer.

ASEA Quintus Rubber-Pad Press

ASEA presses, generally designed with force capacities of 50 to 500 MN (5600 to 56,000 tonf), are constructed of wire-wound frames and have separate guiding columns. By winding the press frames with prestressed wire, only compressional stresses are present in the large castings or forgings of the yokes and columns, even when subjected to maximum forming pressure. Therefore, when the press is loaded, the frame remains in slight compression, and the major structural components never operate in the tensile mode.

The press is equipped with a forged-steel rubber-pad retainer with a replaceable insert to allow for forming at higher pressures. Although the maximum tool height is sacrificed by using these high-pressure inserts, cutting the work area in half doubles the maximum forming pressure of the press when needed.

Standard table sizes range from 0.7 × 1.0 m (28 × 39 in.) to 2 × 3 m (79 × 118 in.). Difficult-to-form materials such as titanium, along with the die, can be heated outside the press by an infrared heater; blanks can also be heated by conduction from the table through the heat transferred through the die (Fig. 32).

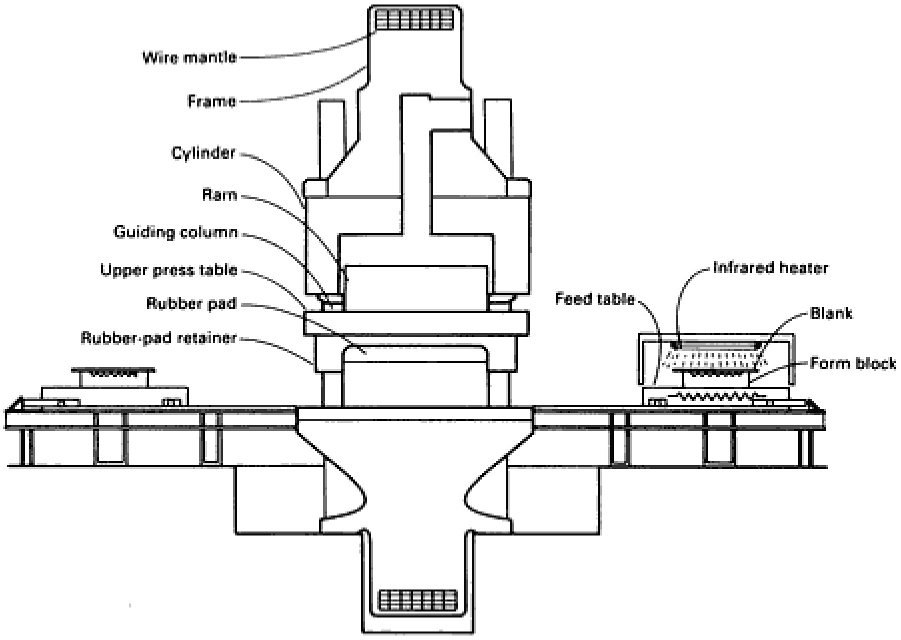


Fig. 32 Schematic of ASEA Quintus rubber-pad press with provision for heating difficult-to-form materials using infrared heater or heating elements contained in feed table

Fluid-Cell Process

Initially developed as the Verson-Wheelon process, this process uses a fluid cell (a flexible bladder, rather than a rubber pad) backed up by hydraulic fluid to exert a uniform pressure directly on the form block positioned on the press table. This process can be classified in terms of the presses used (as for Verson-Wheelon and ASEA Quintus) or as a specialized method (such as the Demarest process) for producing cylindrical and conical parts. The Verson-Wheelon press has cylindrical press housings of laminated, prestressed steel that serve as pressure chambers. The ASEA Quintus press has a forged steel cylinder that is wound with high strength steel wire to create a prestressed press frame with extremely good fatigue properties.

Fluid-cell forming can be used for recessed parts that are beyond the capabilities of rubber-pad forming, for all flange configurations (including C-shaped flanges), and for complex parts with reentrant features and intricate joggles. Maximum form block height is 425 mm (16.7 in.), and typical cycle time is 1 to 2 min.

Verson-Wheelon Process

The Verson-Wheelon process was developed from the Guerin process. It uses higher pressure and is primarily designed for forming shallow parts, using a rubber pad as either the die or punch. A flexible hydraulic fluid cell forces an auxiliary rubber pad to follow the contour of the form block and to exert a nearly uniform pressure at all points.

The distribution of pressure on the sides of the form block permits the forming of wider flanges than with the Guerin process. In addition, shrink flanges, joggles, and beads and fibs in flanges and web surfaces can be formed in one operation to rather sharp detail in aluminum, low-carbon steel, stainless steel, heat-resistant alloys, and titanium.

Presses. The Verson-Wheelon press has a horizontal cylindrical steel housing, the roof of which contains a hydraulic fluid cell (Fig. 33). Fluid-cell bladders can be of neoprene or polyurethane composition. Hydraulic fluid is pumped into the cell, causing it to inflate or expand. The expansion creates the force needed to cause the rubber of the work pad to flow downward, over and around the form block and the metal to be formed.

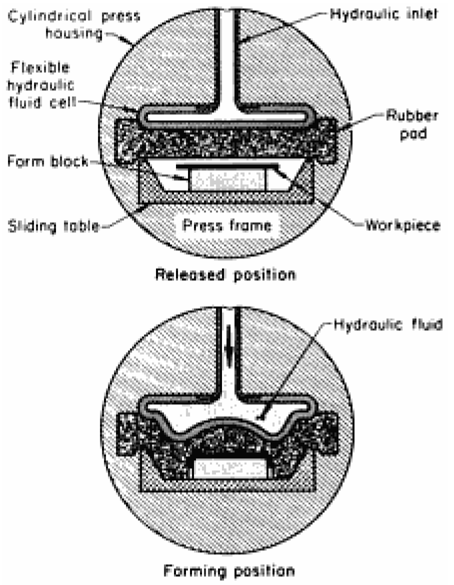

Cylindrical press housing
Hydraulic inlet
Flexible hydraulic fluid cell
Rubber pad
Form block
Sliding table
Press frame
Workpiece
Released position
Hydraulic fluid
Forming position

Fig. 33 Principal components of the Verson-Wheelon process

Below the chamber containing the rubber pad and the hydraulic fluid cell is a passage, extending the length of the press, that is wide and high enough to accommodate a sliding table containing form blocks. At each end of the passage is a sliding table that is moved into position for forming.

Verson-Wheelon presses are available with forming pressures ranging from 35 to 140 MPa (5 to 20 ksi) and force capacities of 22 to 730 MN (2500 to 82,000 tonf). Sliding tables range in size from 508 × 1270 mm (20 × 50 in.) to 1270 × 4170 mm (50 × 164 in.). The larger machine can form parts having flange widths up to 238 mm ($9\frac{3}{8}$ in.).

Demarest Process

This technique uses an expanding or bulging rubber punch (Fig. 34). It is suitable for cylindrical, somewhat spherical, and conical parts. The punch, equipped with a hydraulic cell, is placed inside the workpiece, which is in turn placed inside the die. Hydraulic pressure expands the punch. After forming, the punch is contracted and removed.

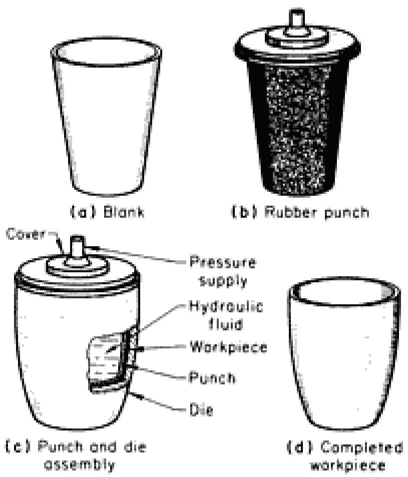

(a) Blank
(b) Rubber punch
Cover
Pressure supply
Hydraulic fluid
Workpiece
Punch
Die
(c) Punch and die assembly
(d) Completed workpiece

Fig. 34 Forming of a fuel-tank section from a blank using the Demarest process

ASEA Quintus Fluid Cell Process

This is another variation of the Guerin process for deeper and more complex parts. It uses a flexible rubber diaphragm backed up by oil as either the male or female tool half. The pressurized diaphragm forces the blanks to assume the shape of the solid-tool halves. The high, uniform, hydrostatic pressure forms shallow- to medium-depth parts with complex shapes to final shape, practically eliminating the subsequent hand forming usually required to apply the Guerin process.

Presses. ASEA Quintus fluid cell presses are available with maximum forming pressures ranging from 100 to 200 MPa (14 to 29 ksi) and force capacities up to 1400 MN (157,000 tonf). The forming tables range in size from 700 × 2000 mm (27.5 × 78.7 in.) to 2000 × 5000 mm (78.7 × 196.8 in.). The large presses can accommodate tools as high as 425 mm (16.7 in.) and consequently form parts as deep or flanges as wide as 425 mm (16.7 in.).

Fluid Forming

In contrast to conventional two-die forming, which produces local stress concentrations in a workpiece, fluid forming (previously classified as rubber-diaphragm forming) is a flexible-die technique that inhibits thinning and crack initiation due to the uniformly distributed pressure. In fluid forming, a rubber diaphragm serves as both the blankholder and a flexible-die member. Fluid forming differs from the rubber-pad and fluid-cell processes in that the forming pressure can be controlled as a function of the draw depth of the part.

Fluid forming was initially known as the *Hydroform* process. The process can use a Verson Hydroform press in which a hydraulic pump delivers fluid under pressure into the pressure-dome cavity. The punch containing the die is driven upward into the cavity against the resistance provided by the fluid, and the workpiece is formed. Fluid forming is intended for punch, cavity, hydroblock, or expansion forming of deep-recessed parts. Cycle time is 15 to 20 s for most parts.

Verson Hydroform Process

This process differs from those previously described in that the die cavity is not completely filled with rubber, but with hydraulic fluid retained by a 64 mm ($2\frac{1}{2}$ in.) thick cup-shaped rubber diaphragm. This cavity is termed the pressure dome (Fig. 35). A replaceable wear sheet is cemented to the lower surface of the diaphragm. This method allows more severe draws than in conventional draw dies because the oil pressure against the diaphragm causes the metal to be held tightly against the sides as well as against the top of the punch.

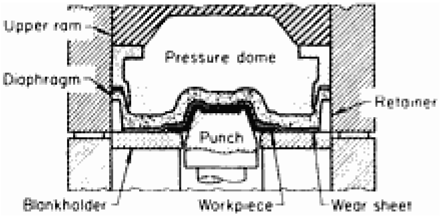


Fig. 35 Fluid-cell forming in a Hydroform press

Reductions in blank diameter of 60 to 70% are common for a first draw. When redrawing is necessary, reductions can reach 40%. Low-carbon steel, stainless steel, and aluminum in thicknesses from 0.25 to 1.65 mm (0.010 to 0.065 in.) are commonly formed. Parts made of heat-resistant alloys and copper alloys are also formed by this process.

SAAB Rubber-Diaphragm Method

In this variation, hydraulic fluid is used behind a comparatively thin rubber pad or diaphragm. A hydraulic piston compresses the fluid against the rubber and forces the blank into the die (Fig. 36).

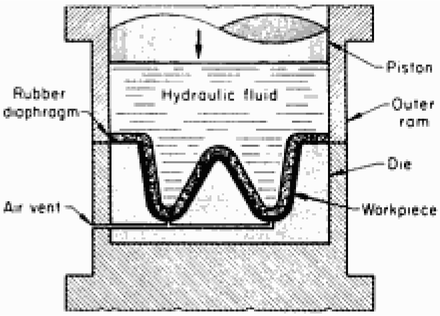

Piston
Rubber diaphragm
Hydraulic fluid
Outer ram
Die
Air vent
Workpiece

Fig. 36 Principals of SAAB rubber-diaphragm (fluid forming) method. The air vents keep trapped air from causing blisters on the workpiece.

ASEA Quintus Fluid Forming Press

This is a vertical press with a circular fluid form unit containing the rubber diaphragm and pressure medium. These modular fluid form units serve the same function as the units used in the ASEA Quintus deep-drawing fluid forming press described below. The rigid tool half may be a male block, a cavity die, or an expansion die situated in a movable tool holder. Blanks are loaded onto the tool holder prior to shuttling the holder into the press for the 10 to 50 s forming cycle required to produce the part.

ASEA Quintus Deep-Drawing Technique

A variation of the SAAB rubber-diaphragm method, ASEA Quintus deep-drawing fluid forming uses two telescopic rams: an outer ram to control dome pressure and an inner ram to regulate the length of the punch draw. Because domes are interchangeable, the user can select a dome of optimal size. Maximum forging pressure can also be increased with smaller domes.

Three-Roll Forming

THREE-ROLL FORMING is used to form plate, sheet, bars, beams, angles, or pipe into various shapes (Fig. 37) by passing the work metal between three properly spaced rolls. Any metal that can be cold formed by other processes can be formed in a three-roll machine.

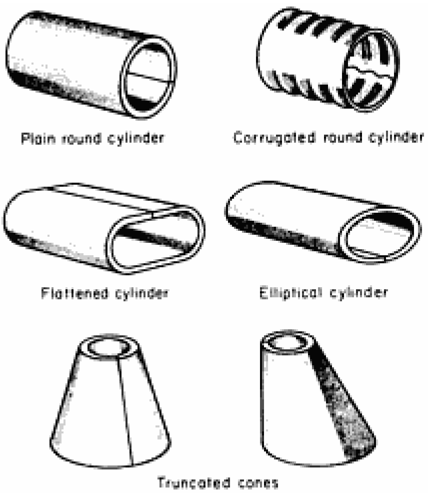

Plain round cylinder
Corrugated round cylinder
Flattened cylinder
Elliptical cylinder
Truncated cones

Fig. 37 Typical shapes produced from flat stock by three-roll forming

Machines

There are two types of three-roll forming machines: the pinch-roll type and the pyramid-roll type. The rolls on most three-roll machines are positioned horizontally; a few vertical machines are used, primarily in shipyards. An advantage of vertical machines in forming scaly plate is that loose scale is less likely to become embedded in the work metal. Vertical rolls, however, handle wide sections that require careful support to avoid skewness in rolling with difficulty. Most vertical machines have short rolls for fast unloading and are used for bending narrow plate, bars, and structural sections.

Conventional pinch-type machines have the roll arrangement shown in Fig. 38. For rolling flat stock up to about 25 mm (1 in.) thick, each roll is of the same diameter. However, on larger machines, the top rolls are sometimes smaller to maintain approximately the same surface speed on both the inside and outside surfaces of the plate being formed. These heavier machines are also supplied with a slip-friction drive on the front roll to permit slip, because of the differential in surface speed of the rolls. Therefore, as work metal thickness increases, the diameter of the top roll is decreased in relation to the diameter of the lower rolls. In general, the smallest cylinder that can be rolled under optimal conditions is 50 mm (2 in.) larger in diameter than the top roll of a pinch-type machine.

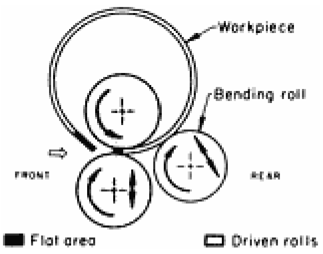


Fig. 38 End view of a cylindrical workpiece being rolled in a conventional pinch-type machine. Note large flat area on leading end, and smaller flat area on trailing end.

Shoe-Type Pinch-Roll Machines. One important modification of the three-roll pinch-type machine is the shoe-type machine, which uses the pinch principle with a forming shoe (Fig. 39). Because of the relationship of the two front rolls and the forming shoe to the workpiece, the flat area becomes barely discernible compared with the length of flat area obtained when rolling in a conventional machine (without preforming). This machine is used to manufacture transformer cases and small tanks, such as jackets for hot water tanks.

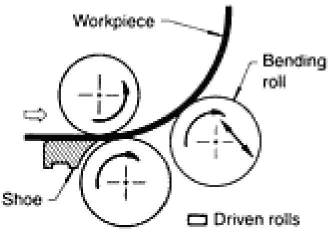


Fig. 39 End view of a cylindrical workpiece being rolled in a shoe-type machine with two powered rolls

In pyramid-type machines (Fig. 40) the bottom rolls are of equal diameter, but about 50% smaller than the top roll. The bottom rolls are gear driven and are normally fixed; each roll is supported by two smaller rolls. The top roll is adjustable vertically to control the diameter of the cylinder formed. The top roll, which rotates freely, depends on friction with the work metal for rotation. Backup rolls are not used on the top roll.

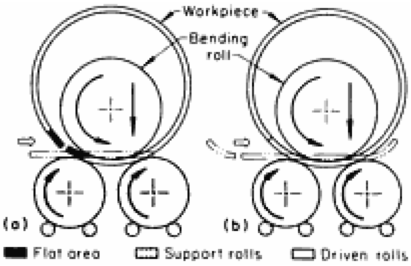


Fig. 40 Arrangement of rolls in a pyramid-type machine. (a) Entrance of flat workpiece and shape of a nearly finished workpiece, including the flat areas on the leading and trailing ends. (b) Similar, except that the workpiece was prebent to minimize the flat areas on the ends.

As shown in Fig. 40, the work metal is placed on the bottom rolls while the top roll is raised. The top roll is then lowered to contact and bend the work metal a predetermined amount, depending on the diameter of the workpiece to be formed. On a pyramid-type machine, the minimum workpiece diameter is rarely less than 150 mm (6 in.) greater than the top roll. However, more power is required to form sheet or plate into cylinders of minimum diameter than to form cylinders substantially larger than the top roll.

Rolls

Rolls for three-roll forming machines are machined from steel forgings having a carbon content of 0.40 to 0.50% and a hardness of 160 to 210 HRB. Plain carbon steel such as 1045 has often been used; when greater strength is needed, rolls are forged from an alloy steel such as 4340.

Contour Roll Forming

CONTOUR ROLL FORMING (also known as roll forming or cold roll forming) is a continuous process for forming metal from sheet, strip, or coiled stock into shapes of uniform cross section by feeding the stock through a series of roll stations equipped with contoured rolls (sometimes called roller dies). With two or more rolls per station, most contour roll forming is done by working the stock progressively in two or more stations until the finished shape is produced.

The process is suited for large quantities and long lengths to close tolerances and involves a minimum of handling. Auxiliary operations, such as notching, slotting, punching, embossing, curving, and coiling, can be combined with contour roll forming.

Contour roll forming is used for parts that were previously manufactured by extrusion processes. This use is limited, however, to parts that can be redesigned to have a constant wall thickness. Industries that use roll-formed products include the automotive; building; office furniture; home appliance and home product; medical; railcar; aircraft; and heating, ventilation, and air conditioning (HVAC) industries.

Contour roll forming can be divided into two broad categories: a process using precut lengths of work metal (precut or cut-to-length method), and a process that uses coil stock that is trimmed to size after forming (post-cut method).

Work Materials

Any material that can withstand bending to the desired radius can be contour roll formed. Thicknesses of 0.13 to 19 mm (0.005 to $\frac{3}{4}$ in.) and material widths of 3.2 to 1830 mm ($\frac{1}{8}$ to 72 in.) can be used. Length of the formed part is limited only by the length that can be handled conveniently after forming.

In some cases, multiple sections can be formed from a single strip; in other cases, several strips can be fed simultaneously into the machine and combined after forming to produce a composite section. Contour roll forming is almost always performed at room temperature; however, some materials, such as certain titanium alloys, must be formed at elevated temperatures. This is done on specially designed machines.

Machines

The machine most commonly used has a number of individual units, each of which is actually a dual-spindle roll-forming machine mounted on a suitable baseplate to make a multiple-unit machine. The flexibility of this construction permits the user to purchase enough units for immediate needs only.

Roll forming machines can be classified according to the method by which the spindles are supported in the unit. Generally, two types exist: inboard (or overhung spindle) machines and outboard machines.

Inboard machines (Fig. 41) have spindle shafts supported on one end that are 25 to 38 mm (1 to 1$\frac{1}{2}$ in.) in diameter and up to 102 mm (4 in.) in length. They are used for forming light-gage moldings, weather strips, and other simple shapes. Material thickness is limited to about 1 mm (0.040 in.), and the top roll shaft is generally geared directly to the bottom shaft. This direct-mesh gearing permits only a small amount of roll redressing (no more than the thickness of the material being formed) on the top and bottom rolls. Tooling changeover is faster on this machine than on the outboard machine.

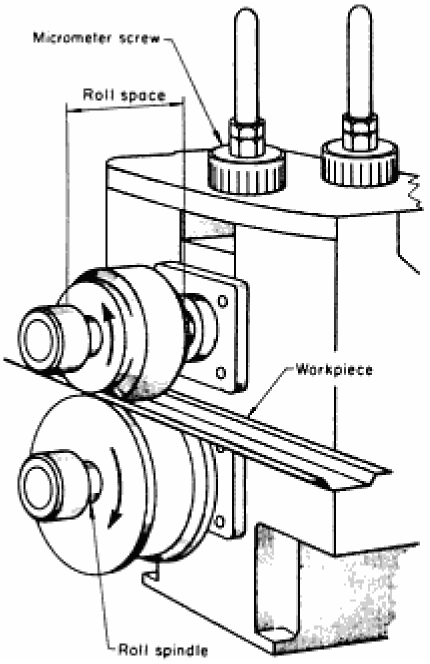


Fig. 41 Overhung-spindle machine (one roll station) for contour roll forming

Outboard machines (Fig. 42) have housings supporting both ends of the spindle shafts. The outboard housing is generally adjustable along the spindles, permitting shortening of the distance between the supports to accommodate the roll forming of small shapes of heavy-gage material. This also permits the machine to be used as an inboard machine when desired. Outboard machines can be readily designed to accommodate any width of material by making the spindle lengths suit the material width and then mounting the individual units and spindles on a baseplate of suitable width. This type of machine is built with spindle sizes ranging from 38 to 102 mm (1$\frac{1}{2}$ to 4 in.) diameter and with width capacities up to 1830 mm (72 in.).

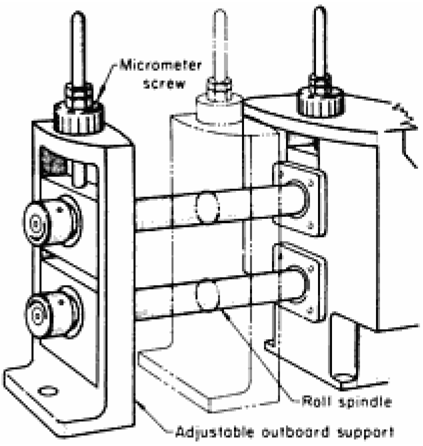


Fig. 42 Universal contour roll forming machine, with outboard support for roll shafts (rolls not shown)

Tooling

Tooling used in roll forming includes the forming rolls and the dies for punching and cutting off the material. Tube mills require some additional tooling to weld, size, and straighten the tubes as they are produced on the machine.

Forming Rolls. The rolls actually form the material as it moves through the machine. Several factors must be considered when designing the rolls to form a particular part. These include the number of required passes, the material width, the "flower" design, the roll design parameters, and the roll material. Flower is the name given to the progressive section contours, starting with the flat material and ending with the desired section profile.

Roll Materials. The materials that are most commonly used for contour rolls are: low-carbon steel, turned and polished but not hardened; gray iron (such as class 30), turned and polished but not hardened; low-alloy tool steel (such as O1 or L6), hardened to 60 to 63 HRC and sometimes chromium plated; high-carbon high-chromium tool steel (such as D2), hardened to 60 to 63 HRC and sometimes chromium plated; and bronze (usually aluminum bronze).

Drop Hammer Forming

DROP HAMMER FORMING is a process for producing shapes by the progressive deformation of sheet metal in matched dies under the repetitive blows of a gravity drop hammer or a power drop hammer. Configurations most commonly formed by the process include shallow, smoothly contoured, double-curvature parts; shallow-beaded parts; and parts with irregular and comparatively deep recesses. Small quantities of cup-shape and box-shape parts, curved sections, and contoured flanged parts also are formed.

Advantages and Limitations

The main advantages of drop hammer forming are: (a) low cost for limited production; (b) relatively low tooling costs; (c) dies that can be cast from low-melting alloys and that are relatively simple to make; (d) short delivery time of product because of simplicity of toolmaking; and (e) the possibility of combining coining with forming.

Against these advantages, the following limitations must be weighed: (a) probability of forming wrinkles; (b) need for skilled operators, specially trained for this process; (c) restriction to relatively shallow parts with generous radii; (d) restriction to relatively thin sheet, from about 0.61 to 1.6 mm (0.024 to 0.064 in.) (thicker sheet can be formed only if the parts are shallow and have generous radii).

Drop hammer forming is not a precision forming method; tolerances of less than 0.8 to 1.6 mm ($\frac{1}{32}$ to $\frac{1}{16}$ in.) are not practical.

Hammers for Forming

Gravity drop hammers and power drop hammers are comparable to a single-action press. However, they can be used to do the work of a press equipped with double-action dies through the use of rubber pads, beads in the die surfaces, draw rings, and other auxiliary equipment.

Because they can be controlled more accurately and because their blows can be varied in intensity and speed, power drop hammers, particularly the air-actuated types, have virtually replaced gravity drop hammers. A typical air drop hammer, equipped for drop hammer forming, is shown in Fig. 43.

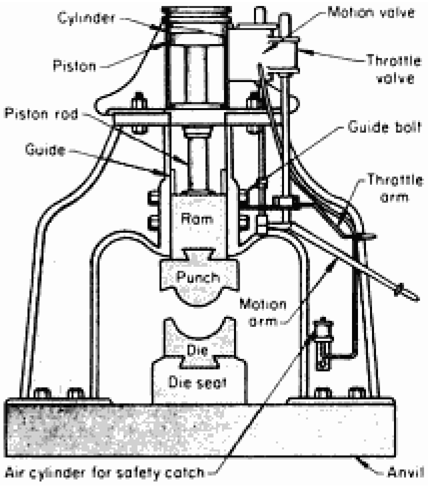


Fig. 43 Air-actuated power drop hammer equipped for drop hammer forming

Tooling

In general, a tool set consists of a die that conforms to the outside shape of the desired part, and a punch that conforms to the inside contour (see Fig. 43).

Tool Materials. Dies are cast from zinc alloy (3.5% Cu, 4% Al, and 0.04% Mg), aluminum alloy, beryllium copper, ductile iron, or steel. The wide use of zinc alloy as a die material stems from the ease of casting it close to the final shape desired. Its low melting point (381 °C, or 717 °F) also is advantageous. All dies, regardless of die material, are polished.

Punches usually are made of lead or a low-melting alloy, although zinc or a reinforced plastic also may be used. The sharpness of the contours to be formed, the production quantity, and the accuracy desired primarily govern the choice of punch material. As a punch material, lead has the advantage of not having to be cast accurately to shape, because it deforms to assume the shape of the die during the first forming trial with a blank.

Lubricants

Lubricants are used in drop hammer forming to facilitate deformation by reducing friction and minimizing galling and sticking, and to preserve or improve surface finish. Selection of a lubricant depends primarily on type of work metal, forming temperature, severity of forming, and subsequent processing. Recommendations for lubricants used with steels and aluminum, magnesium, and titanium alloys are given in the section "Selection and Use of Lubricants in Forming Sheet Metal" in this article.

Explosive Forming

EXPLOSIVE FORMING changes the shape of a metal blank or preform by the instantaneous high pressure that results from the detonation of an explosive. This discussion deals only with the explosives generally termed high explosives, and not with so-called low explosives. Metal tubing up to 1.4 m (54 in.) in diameter in lengths up to 4.6 m (15 ft) is formed using this process. Tubing with diameters of 1.4 m (54 in.) or less can be as long as 9.1 m (30 ft). Typical domes constructed of 6- to 12-piece gore sections fabricated from explosively formed metal can measure up to 6.1 m (20 ft) in diameter. The process has been used to fabricate gore sections for a 12 m (40 ft) diameter dome.

Confined and Unconfined Systems

Systems used for explosive-forming operations are generally classified as either confined or unconfined.

Confined systems (Fig. 44) use a die, in two or more pieces, that completely encloses the workpiece. The closed system has distinct advantages for forming thin stock to close tolerances. It has been used for close-tolerance sizing of thin-wall tubing. However, confined systems are generally used only for comparatively small workpieces because economic feasibility decreases as the size of the workpiece increases.

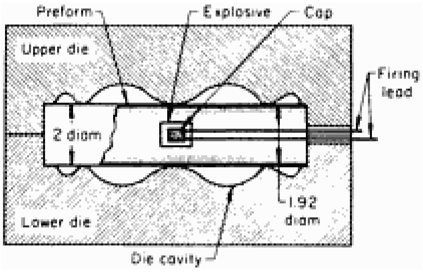

Preform
Explosive
Cap
Upper die
Firing lead
2 diam
1.92 diam
Lower die
Die cavity

Fig. 44 Confined system for explosive forming

In an unconfined system (Fig. 45) the shock wave from the explosive charge takes the place of the punch in conventional forming. A single-element die is used with a blank held over it, and the explosive charge is suspended over the blank at a predetermined distance (the standoff distance). The complete assembly can be immersed in a tank of water, or a plastic bag filled with water can be placed over the blank.

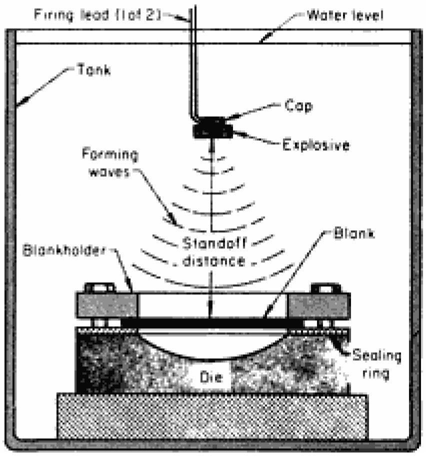

Firing lead (1 of 2)
Water level
Tank
Cap
Explosive
Forming waves
Standoff distance
Blankholder
Blank
Sealing ring
Die

Fig. 45 Unconfined system for explosive forming

Equipment

The primary equipment for explosive forming in an unconfined system consists of a water tank, a crane, a vacuum pump, and a detonator control (firing) box.

The water tank must withstand the repeated impacts of the explosive shock without rupturing. Many tanks are large enough to reduce the shocks reaching the walls from centrally placed charges.

A crane is usually needed to move material around the facility, as well as in and out of the water tank. Ideally, the crane should be air operated to avoid electric power lines within the firing area.

A vacuum pump may be needed for explosive-forming operations in which parts are formed under water. If the firing area is to be maintained with a minimum of electric lines, an entire pump operating on water pressure will work satisfactorily. A mechanical pump driven by an electric motor can be used; the vacuum lines are brought into the firing area from a remote pumping site. An electrically driven mechanical pump is preferred over a venturi pump for its considerably greater capacity and is economy.

Detonation Circuit. Under ideal conditions, the firing box for the electric blasting caps in the only electric device that should be permitted in the area where explosives are handled. A firing box should be constructed on the fail-safe principle so that any malfunction will immediately cause the circuit to be disarmed.

Die Systems and Materials

Basic differences between tooling for explosive forming and for conventional forming arise from the type of loading that the die material must withstand. In explosive forming, high-impact loads transmit shock waves through the metal that cause unusual stress patterns within the die materials. Therefore, corners should be eliminated where possible. Shock loading causes the die to fracture along lines from the corners, rather than through the thinnest section, as in static fracture (Fig. 46).

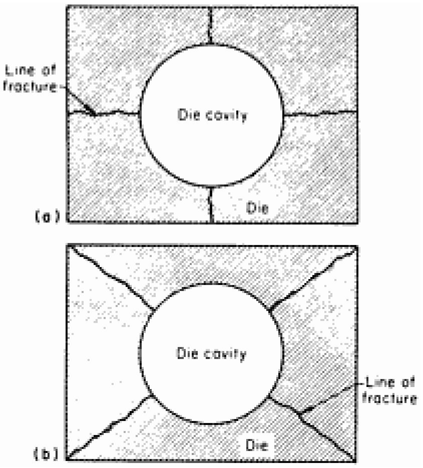


Fig. 46 Modes of fracture of a rectangular die under (a) static load and (b) shock load

Die Materials. Solid dies made from heat-treated alloy steel maintain contour, surface finish, and dimensional accuracy for a relatively long time. To avoid brittle fracture under overloads, a maximum hardness of 50 HRC is desirable.

Electromagnetic Forming

ELECTROMAGNETIC FORMING (EMF) is widely used to both join and shape metals and other materials rapidly and precisely, and without the heat effects and tool marks associated with other techniques. Also known as magnetic pulse forming, EMF uses the direct application of a pressure created in an intense, transient magnetic field. Without mechanical contact, a metal workpiece is formed by the passage of a pulse of electric current through a forming coil.

The major application of EMF is the single-step assembly of metal parts to each other or to other components, although it is also used to shape metal parts. Within the transportation industry, for example, one automotive producer assembles aluminum driveshafts without welding to save a significant amount of weight in light trucks and vans in order to meet requirements for reduced energy consumption. Using the EMF process allows the joining of an impact-extruded aluminum yoke to a seamless tube without creating the heat-affected zone associated with welding.

EMF also is used to expand, compress, or form tubular shapes. It is occasionally used to form flat sheet, and it is often used to combine several forming and assembly operations into a single step. In the automotive industry, EMF is used by all three major U.S. manufacturers and several foreign producers to assemble components such as air conditioner accumulators, high-pressure hoses, shock absorber dust covers, rubber boots on constant velocity (CV) joints, oil cooler heat exchangers, steering wheels, gasoline fill tubes, and accessory motor packages.

Process Description

In its simplest form, EMF uses a capacitor bank, a forming coil, a field shaper, and an electrically conductive workpiece to create intense magnetic fields to do useful work. This very intense magnetic field, produced by the discharge of a bank of capacitors into a forming coil, lasts only a few microseconds. The resulting eddy current that are induced in the conductive workpiece that is placed close to the coil interact with the magnetic field to cause mutual repulsion between the workpiece and the forming coil. The force of this repulsion is sufficient to cause permanent deformation.

The basic circuit (Fig. 47) used for electromagnetic compression forming of a tubular workpiece consists of a forming coil, an energy-storage capacitor, switches, and a power supply of nearly constant current to charge the capacitor. Figure 47(a) shows the flux-density pattern of the magnetic field produced by discharging the capacitor through the forming coil in the absence of an electrically conductive workpiece. The evenly spaced flux lines indicate a uniform flux density within the coil. Figure 47(b) shows the change in field pattern that results when the capacitor is discharged through a forming coil in which a tubular workpiece of highly conductive metal has been inserted. The magnetic field is distorted and the flux density intensified (flux lines are more closely spaced) by confinement to the small annular space between the coil and the workpiece.

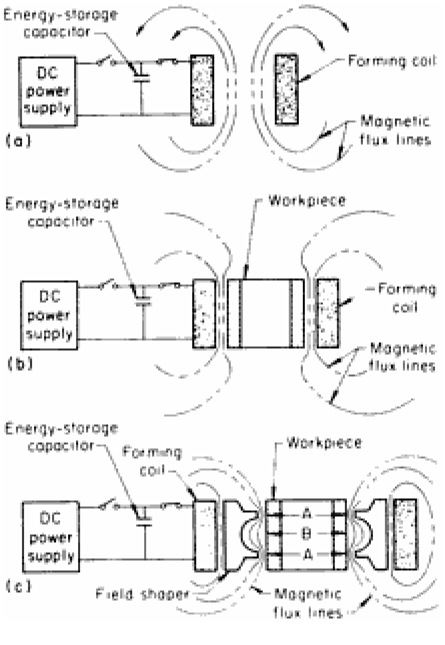


Fig. 47 Basic circuit and magnetic field patterns for electromagnetic compression forming of a tubular workpiece. (a) Field pattern in absence of workpiece. (b) Field pattern with workpiece in forming coil. (c) Field pattern when field shaper is used. A, high pressure; B, low pressure.

Field shapers, which are massive current-carrying conductors inductively coupled to the forming coil, concentrate the magnetic field at the point at which forming is desired. This technique most efficiently uses stored energy to produce high local forming pressures in desired areas. Field shapers also allow the use of a standard forming coil for a variety of applications. The field shaper, which is simpler to make, can be tailored to the specific part to be formed.

Figure 47(c) illustrates the use of a field shaper to concentrate the force in certain regions of the workpiece. This technique not only produces high local forming pressures in desired areas, but also lengthens the life of the forming coil by preventing high pressures on weaker parts of the coil.

Forming Methods. Electromagnetic forming can usually be applied to three forming methods: compression, expansion, and contour forming. As shown in Fig. 48(a), a tubular workpiece is compressed by an external coil, usually against a grooved or suitably contoured insert, plug, tube, or fitting inside the workpiece. The tubular workpiece is expanded by an internal coil (Fig. 48b), usually against a collar or other component surrounding the workpiece. Flat stock is almost always contour-formed against a die (Fig. 48c).

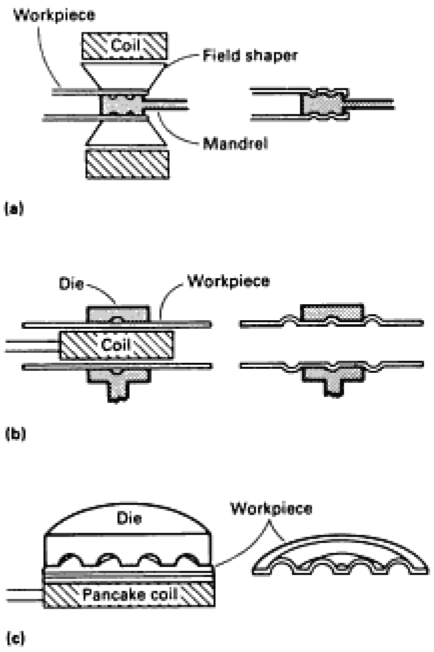


Fig. 48 Three basic methods of EMF. (a) Compression. (b) Expansion. (c) Contour forming

Superplastic Forming (SPF)

SUPERPLASTICITY refers to the ability of certain metals to develop extremely high tensile elongations at elevated temperatures and under controlled rates of deformation. The tensile ductility of superplastic metals typically ranges from 200 to 1000% elongation, but ductilities in excess of 5000% have been reported. Elongations of this magnitude are one to two orders greater than those observed for conventional metals and alloys, and they are more characteristic of plastics than metals.

Because the capabilities and limitations of sheet metal fabrication are most often determined by the tensile ductility limits, significant advantages potentially are available for forming such materials, provided the high-ductility characteristics observed in the tensile test can be used in production forming processes.

Superplastic Alloys

There are several different types of superplasticity in terms of the microstructural mechanisms and deformation conditions, including the following: micrograin superplasticity, transformation superplasticity, and internal stress superplasticity. At this time, only the micrograin superplasticity is of importance in the fabrication of parts. For micrograin superplasticity, the high ductilities are observed under the following conditions:

- Very fine grain size material (approximately 10 μm, or 400 μin.)
- Relatively high temperature (greater than about one-half the absolute melting point)
- A controlled strain rate, usually 0.0001 to 0.01 s^{-1}

Because of these requirements, only a limited number of commercial alloys are superplastic. These include Zn-22Al and the titanium and aluminum alloys listed in Table 10. Other alloys, including some ferrous alloys (e.g., hypereutectoid high-carbon steels), exhibit superplastic behavior, but very few of these have been produced commercially.

Table 10 Superplastic properties of aluminum and titanium alloys

Alloy	Test temperature		Strain rate, s^{-1}	Strain rate sensitivity, m [(a)]	Elongation, %
	°C	**°F**			
Aluminum					
Statically recrystallized					
Al-33Cu	400-500	752-930	8×10^{-4}	0.8	400-1000
Al-4.5Zn-4.5Ca	550	1020	8×10^{-3}	0.5	600
Al-6 to 10Zn-1.5Mg-0.2Zr	550	1020	10^{-3}	0.9	1500
Al-5.6Zn-2Mg-1.5Cu-0.2Cr	516	961	2×10^{-4}	0.8-0.9	800-1200
Dynamically recrystallized					
Al-6Cu-0.5Zr (Supral 100)	450	840	10^{-3}	0.3	1000
Al-6Cu-0.35Mg-0.14Si (Supral 220)	450	840	10^{-3}	0.3	900
Al-4Cu-3Li-0.5Zr	450	840	5×10^{-3}	0.5	900
Al-3Cu-2Li-1Mg-0.2Zr	500	930	1.3×10^{-3}	0.4	878
Titanium					
α/β					
Ti-6Al-4V	840-870	1545-1600	1.3×10^{-4} to 10^{-3}	0.75	750-1170
Ti-6Al-5V	850	1560	8×10^{-4}	0.70	700-1100
Ti-6Al-2Sn-4Zr-2Mo	900	1650	2×10^{-4}	0.67	538
Ti-4.5Al-5Mo-1.5Cr	871	1600	2×10^{-4}	0.63-0.81	>510
Ti-6Al-4V-2Ni	815	1499	2×10^{-4}	0.85	720
Ti-6Al-4V-2Co	815	1499	2×10^{-4}	0.53	670
Ti-6Al-4V-2Fe	815	1499	2×10^{-4}	0.54	650
Ti-5Al-2.5Sn	1000	1830	2×10^{-4}	0.49	420
β **and near** β					
Ti-15V-3Cr-3Sn-3Al	815	1499	2×10^{-4}	0.5	229
Ti-13Cr-11V-3Al	800	1470	. . .	. . .	<150
Ti-8Mn	750	1380	. . .	0.43	150
Ti-15Mo	800	1470	. . .	0.60	100
α					
CP Ti	850	1560	1.7×10^{-4}	. . .	115

(a) The strain rate sensitivity exponent m indicates the rate of change of flow stress with strain rate. It is defined by $m = \Delta \ln \sigma / \Delta \ln \dot{\epsilon}$ where σ is the flow stress and $\dot{\epsilon}$ is the strain rate

Superplastic Forming Processes

Blow forming and vacuum forming are basically the same process (sometimes called stretch forming) in that a gas pressure differential is imposed on the superplastic diaphragm, causing the material to form into the die configuration. In vacuum forming, the applied pressure is limited to atmospheric pressure (100 kPa, or 15 psi), and the forming rate and capability are therefore limited. With blow forming, additional pressure is applied from a gas pressure reservoir, and the only limitations are related to the pressure rating of the system and the pressure of the gas source. A maximum pressure of 690 to 3400 kPa (100 psi to 500 psi) is typically used in this process.

In blow forming (Fig. 49) the dies and sheet material are normally maintained at the forming temperature, and the gas pressure is imposed over the sheet, causing the sheet to form into the lower die; the gas within the lower die chamber is simply vented to atmosphere. The lower die chamber also can be held under vacuum, or a back pressure can be imposed to suppress cavitation if necessary.

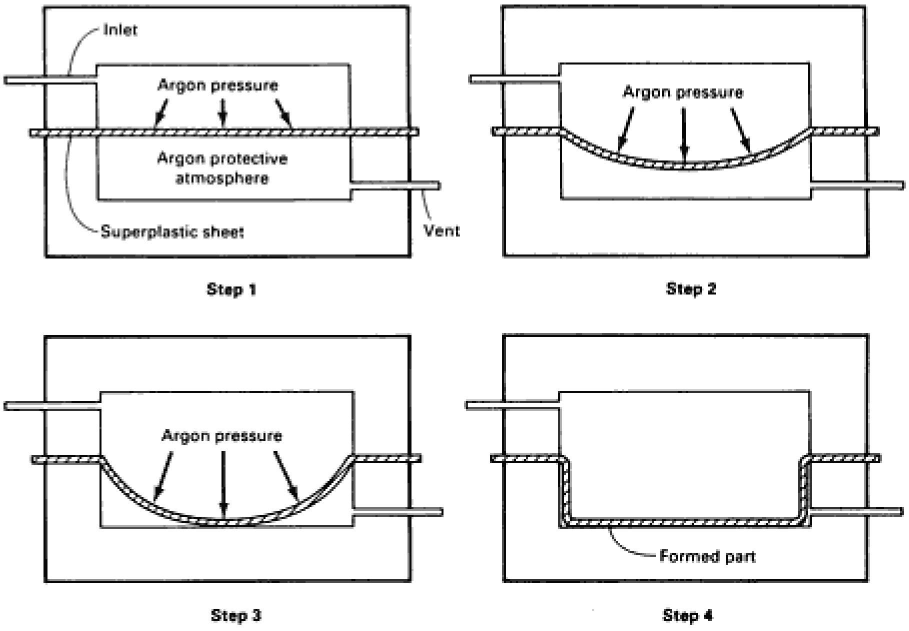

Inlet
Argon pressure
Argon protective atmosphere
Superplastic sheet
Vent
Step 1
Argon pressure
Step 2
Argon pressure
Step 3
Formed part
Step 4

Fig. 49 Schematic of the blow forming technique for superplastic forming

The periphery of the sheet is held in a fixed position and does not "draw-in," as would be the case in typical deep-drawing processes. It is common to use a raised land (seal bead) machined into the tooling around the periphery (Fig. 50) to secure the sheet from slippage and draw-in and to form an airtight seal to prevent leakage of the forming gas. Therefore, the sheet alloy stretches into the die cavity, and all of the material used to form the part comes from the sheet overlying the die cavity. This thins the sheet considerably for complex and deep-drawn parts; it also can create significant gradients in the thickness in the finished part.

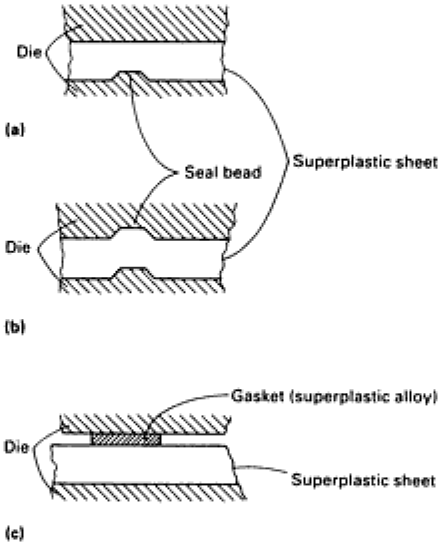

Die
(a)
Seal bead
Superplastic sheet
Die
(b)
Gasket (superplastic alloy)
Die
Superplastic sheet
(c)

Fig. 50 Various sealing methods that have been used around the sheet to provide a pressure seal suitable for containing the gas pressure during forming. Sections (a) and (b) utilize seal beads machined into the tooling, and (c) shows the use of a superplastic frame used as a soft gasket.

This process is used to fabricate structural and ornamental parts from titanium, aluminum, and other metals. For titanium alloys, forming is carried out at about 900 °C (1650 °F). Large, complex parts can be formed by this method; it has the advantage of no moving die components (that is, no double-acting mechanisms) and does not require mated dies. Multiple parts can be formed in a single process cycle, thus increasing the production rate for some parts.

Thermoforming has been adapted from plastics technology for forming superplastic metals. These methods sometimes use a moving or adjustable die member in conjunction with gas pressure or vacuum. Figure 51 shows two variations of thermoforming methods. In one variation, an undersize male die punch is used to stretch-form the superplastic sheet, followed by application of gas pressure to force the sheet material against the configurational die to complete the shaping operation. In another method, the first step involves blowing a bubble in the sheet away from the tool. The male tool is then moved into the bubble, and the pressure is reversed to cause the bubble to conform to the shape of the tool.

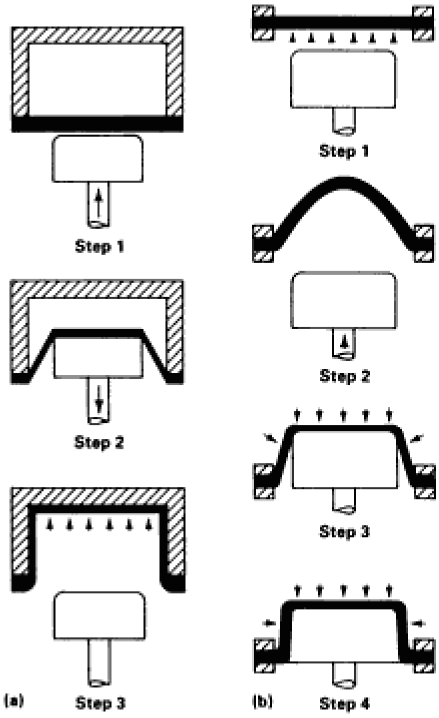


Fig. 51 Examples of thermoforming methods used for superplastic forming. (a) Plug-assisted forming into a female die cavity. (b) Snap-back forming over a male die that is moved up into the sheet

Two additional alternatives methods use a movable die member to aid in prestretching the sheet material before gas pressure is applied (Fig. 52). In this case, the gas pressure is applied from the same side of the sheet as the moving die. These techniques provide ways of producing different shapes of parts and are effective for controlling the thinning characteristics of the finished part.

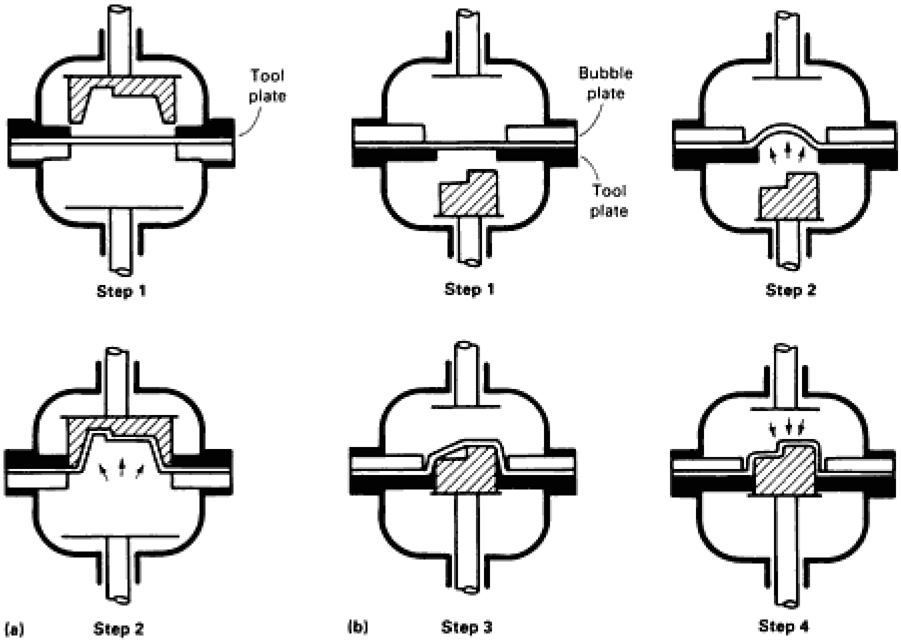


Fig. 52 Thermoforming methods that use gas pressure and movable tools to produce parts from superplastic alloys. (a) Female forming. (b) Male forming

SPF/DB Processes. Joining methods, such as diffusion bonding (DB), can be combined with superplastic forming; these processes are generally referred to as SPF/DB. Although diffusion bonding is not a sheet metal process, it complements and enhances superplastic forming to such an extent that the two processes must be discussed together.

SPF/DB evolved as a natural combination because the process temperature requirements of both are similar. The low flow properties characteristic of the superplastic alloys aid the DB pressure requirements. Many superplastic alloys can be diffusion bonded under pressures in the same low range as that used for SPF processing (that is, approximately 2100 to 3400 kPa, or 300 to 500 psi). The SPF method most used with SPF/DB is blow forming.

SPF/DB includes several variations:

- Forming of a single sheet onto preplaced details, followed by diffusion bonding (Fig. 53)
- Diffusion bonding two sheets at selected locations, followed by the forming of one or both into a die (Fig. 54). The reverse sequence can be used.
- Diffusion bonding of three or more sheets at selected locations under gas pressure, followed by expansion under internal gas pressure, which forms the outer two sheets into a die. In the process, the center sheet(s) is (are) stretched into a core configuration (Fig. 55).

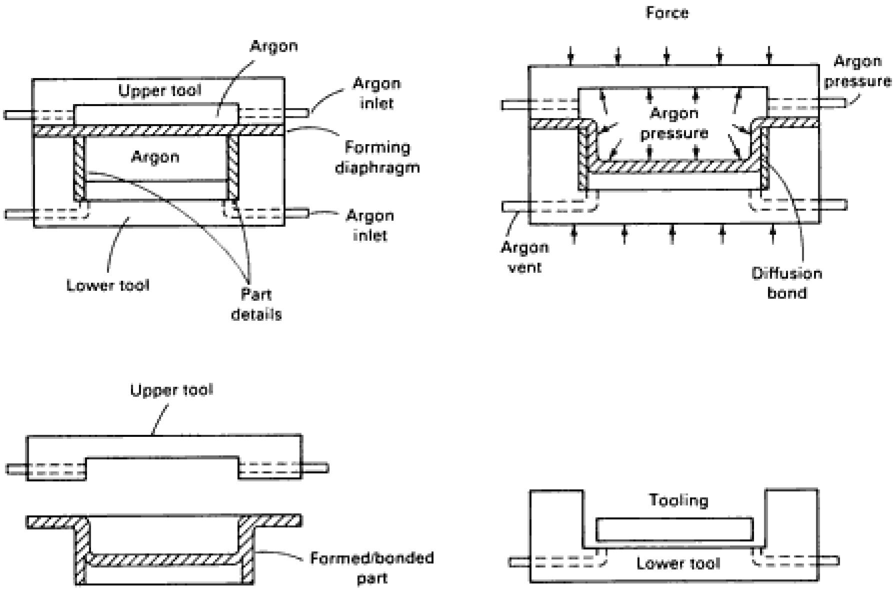

Argon
Upper tool
Argon inlet
Argon
Forming diaphragm
Argon inlet
Lower tool
Part details
Force
Argon pressure
Argon pressure
Argon vent
Diffusion bond
Upper tool
Formed/bonded part
Tooling
Lower tool

Fig. 53 Cross section of the SPF process combined with diffusion bonding (SPF/DB). The process shown utilizes pre-placed details to which the superplastic sheet is bonded.

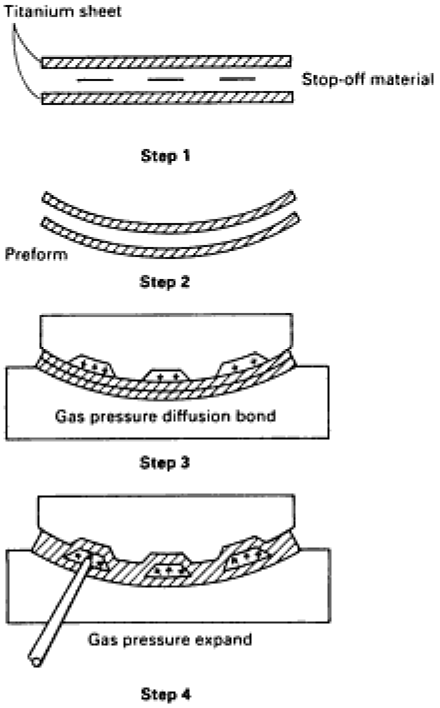

Titanium sheet
Stop-off material
Step 1
Preform
Step 2
Gas pressure diffusion bond
Step 3
Gas pressure expand
Step 4

Fig. 54 Operations required for joining two sheets of superplastic alloy using the SPF/DB process

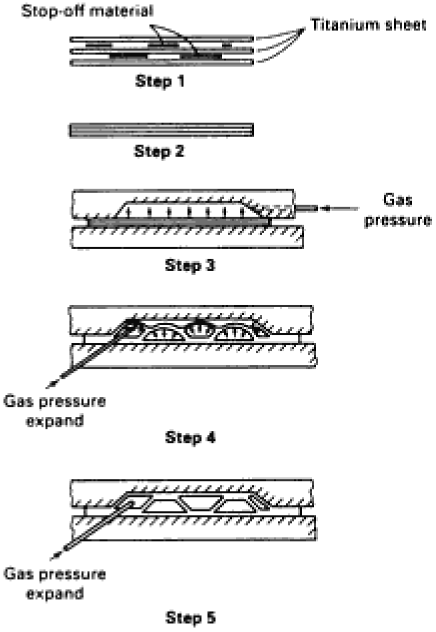

Stop-off material
Titanium sheet
Step 1
Step 2
Gas pressure
Step 3
Gas pressure expand
Step 4
Gas pressure expand
Step 5

Fig. 55 Operations required for joining three sheets of superplastic alloy using the SPF/DB process

A variation of the above method uses a minimum of four sheets to make a sandwich panel. As the skin sheets are expanded, the inner two sheets are bonded to define the core structure; finally the core is expanded to bond with the external sheets and to complete formation of the sandwich structure (Fig. 56).

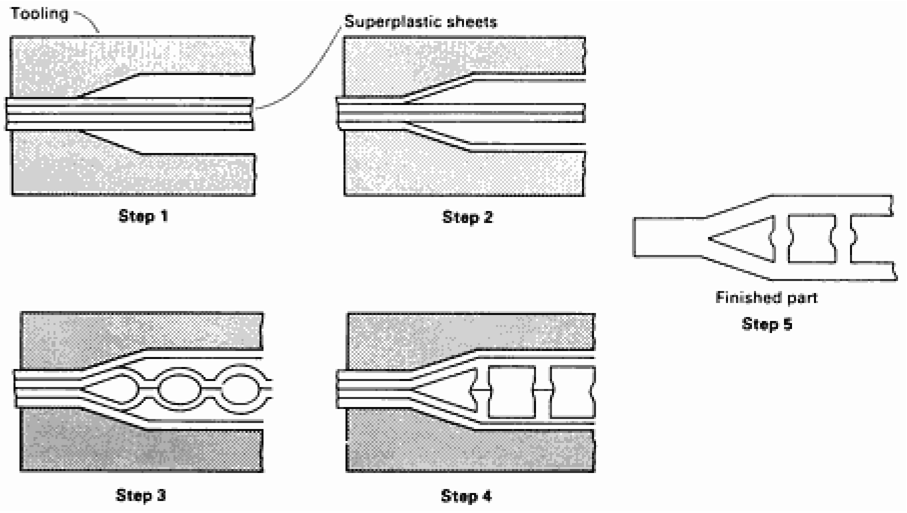

Tooling
Superplastic sheets
Step 1
Step 2
Finished part
Step 5
Step 3
Step 4

Fig. 56 Example of a four-sheet SPF/DB process in which the outer sheets are formed first and the center sheets are then formed and bonded to the outer two sheets.

Forming Equipment and Tooling

The forming of superplastic sheet materials involves methods that are different from those used in other forming processes. The environmental conditions, the equipment, and tooling are different.

Forming Equipment. For blow forming and vacuum forming, the forming tools must be constrained to counteract the forming gas pressure. In addition, a seal is needed at the interface between the sheet and the tool around the periphery to prevent loss of the gas pressure.

Hydraulic presses and mechanical clamping systems have been used. The hydraulic press can be loaded and unloaded fairly rapidly, but it requires a significant capital investment. The mechanical clamping systems are much less expensive, but are more cumbersome to load and unload. Recently, robotic systems have been coupled with a hydraulic press to aid the loading and unloading. This system is especially beneficial for high-temperature SPF of titanium alloys.

The hydraulic presses used include both single-action and multiple-action systems. The single-action press applies constraining pressure only. The multiple-action press can also move dies into the forming sheet and effectively aid in the control of the thinning gradients.

Tooling Materials. The tooling used in SPF is heated to the forming temperature and subjected to internal gas pressure and pressing clamping loads. The internal gas pressure is typically less than 3400 kPa (500 psi), which usually is not the critical design factor for SPF tools. More important are the clamping loads and thermal stresses encountered during heat-up and cool-down and the environmental conditions. Thermal stresses can cause permanent distortions in the die; this is controlled by selecting a material with high strength and creep resistance at the forming temperature. Slow heating and cooling of the tooling can reduce the thermal stresses. Materials with a low coefficient of thermal expansion and those that do not undergo a phase transformation during heating and cooling are preferred for high-temperature SPF. Various metals and alloys, graphite, and ceramics have been used as tool materials.

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Hammers and Presses for Forging

FORGING MACHINES fall into three categories according to their method of operation. Mechanical forging presses are classified as *stroke-restricted machines;* the ability of mechanical presses to deform the work is determined by the length of the press stroke and the available force at various stroke positions. Hydraulic presses are *force-restricted machines* because their ability to deform the material depends on the maximum force rating of the press. *Energy-restricted machines,* including hammers and high-energy-rate forging machines, deform the workpiece by the kinetic energy of the hammer ram. Screw-type presses, although similar in construction to mechanical and hydraulic presses, are classified as energy-restricted machines.

Some of these machines can be used for many forging processes, such as open-die forging and impression-die (or closed-die) forging. Others are restricted to specific processes.

Hammers

Forging processes using hammers are the most versatile and the least expensive of all forging processes. Hammers are used primarily in hot forging and coining. Basically, the two types of hammers are gravity drop and power drop, with several variations of each type. In hammer forging, the workpiece, usually a heated bar, billet, bloom, or ingot, is placed on the lower die and struck by the upper die and ram, causing it to deform plastically with each successive blow. Although all hammers operate on the principle of high impact, designs vary, depending on the method of actuation. Table 1 compares the capacities of various types of hammers.

Table 1 Capacities of various types of forging hammers

Type of hammer	Ram weight		Maximum blow energy		Impact speed		Number of blows per minute
	kg	**lb**	**kJ**	**ft · lb**	**m/s**	**ft/s**	
Board drop	45-3,400	100-7,500	47.5	35,000	3-4.5	10-15	45-60
Air or steam lift	225-7,250	500-16,000	122	90,000	3.7-4.9	12-16	60
Electrohydraulic drop	450-9,980	1,000-22,000	108.5	80,000	3-4.5	10-15	50-75
Power drop	680-31,750	1,500-70,000	1,153	850,000	4.5-9	15-30	60-100

Gravity-Drop Hammers

The main components of a gravity-drop hammer are the anvil or base, supporting columns that contain the ram guides, and a device that returns the ram to its starting position. The energy that deforms the workpiece is derived from the downward drop of the ram. The height of the fall and the weight of the ram determine the force of the blow.

Board-drop hammers (Fig. 1) are widely used, especially for producing forgings weighing no more than a few pounds. In the board-drop hammer, the ram is lifted by one or more boards keyed to it and passed between two friction rolls at the top of the hammer. The boards are rolled upward and then mechanically released, permitting the ram to drop from the desired height. Power for lifting the ram is supplied by one or more motors. The hammers have falling weights, or rated sizes, of 180 to 4500 kg (400 to 10,000 lb); standard sizes range from 450 to 2250 kg (1000 to 5000 lb), in increments of approximately 225 and 455 kg (500 and 1000 lb). The height of fall of the ram varies with hammer size, ranging from approximately 900 mm (35 in.) for a 180 kg (400 lb) hammer to approximately 2 m (75 in.) for a 3400 kg (7500 lb) hammer. The height of fall, and thus the striking force, of the hammer is approximately constant for a given setting and cannot be altered without stopping the machine and adjusting the length of stroke. Anvils on board-drop hammers are 20 to 25 times as heavy as the rams.

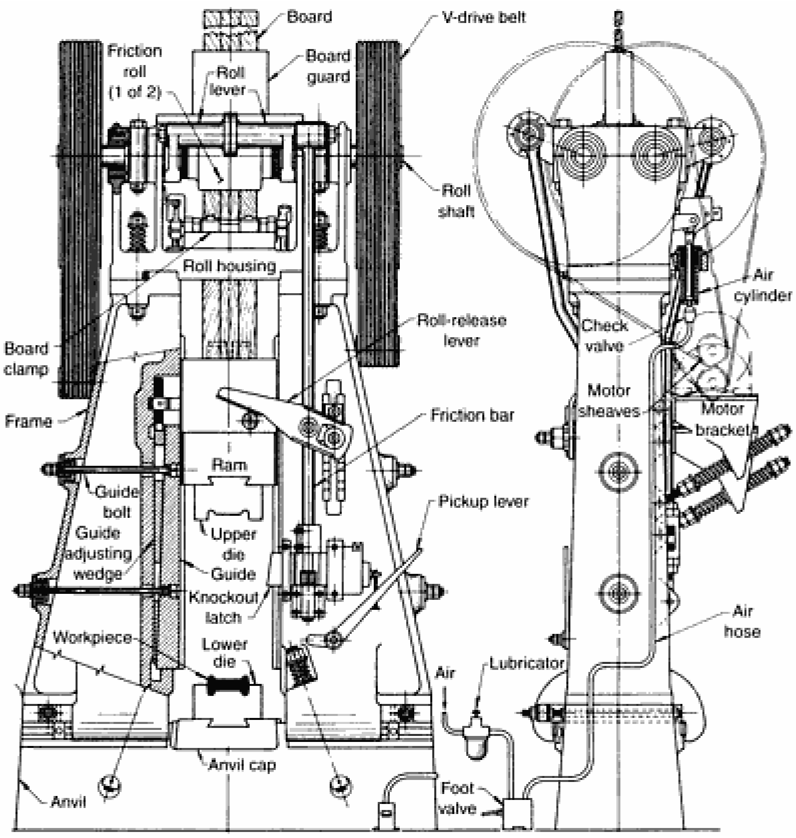

Board
V-drive belt
Friction roll (1 of 2)
Roll lever
Board guard
Roll shaft
Roll housing
Air cylinder
Roll-release lever
Check valve
Board clamp
Motor sheaves
Motor bracket
Frame
Friction bar
Ram
Guide bolt
Guide adjusting wedge
Upper die
Guide
Pickup lever
Knockout latch
Workpiece
Lower die
Air hose
Air
Lubricator
Anvil cap
Foot valve
Anvil

Fig. 1 Principal components of a board-drop hammer

The air-lift, gravity-drop hammer is similar to the board drop hammer in that the forging force is derived from the weight of the falling ram assembly and upper die. It differs in that the ram is raised by air, steam, or hydraulic power. The size of an air-lift hammer generally ranges from approximately 225 to 4500 kg (500 to 10,000 lb). Maximum forging-weight capabilities for drop hammers and board hammers are comparable.

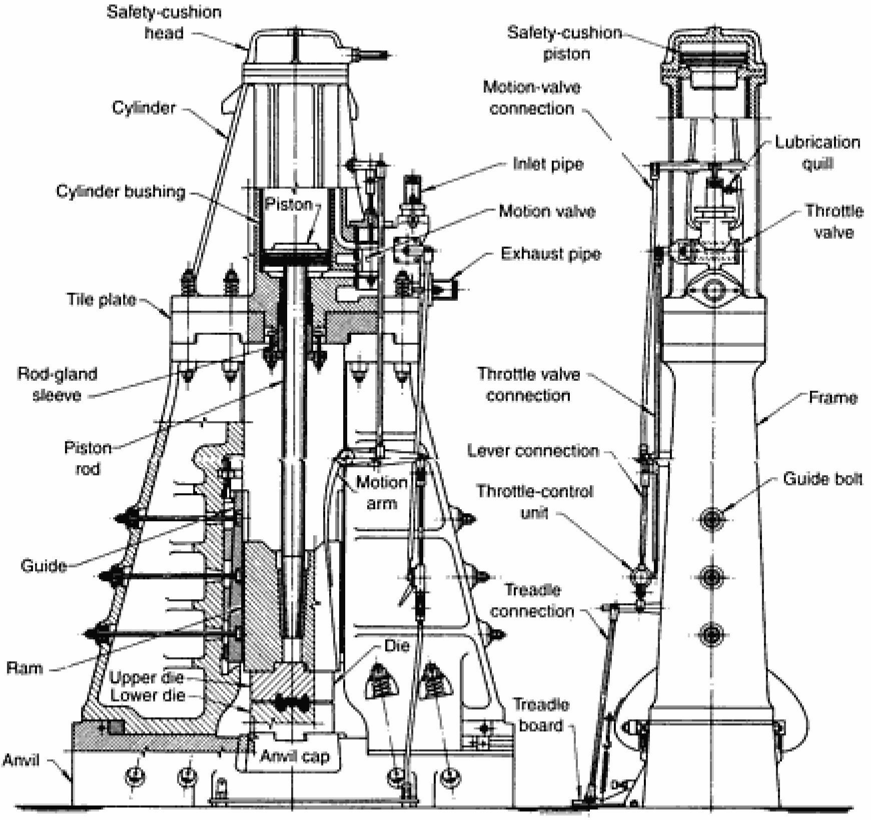
Hydraulic-Lift, Gravity-Drop Hammers. During recent years two significant innovations have been introduced in hammer designs. The first is the electrohydraulic gravity-drop hammer in which the ram is lifted with oil pressure against an air cushion. The compressed air slows down the upstroke of the ram and contributes to its acceleration during the downstroke blow. Thus, the electrohydraulic drop hammer also has a minor power-hammer action. The size of a typical hydraulic-lift hammer is about the same as for air-lift equipment.

The second innovation is the use of electronic blow-energy control. This allows the user to program the drop height of the ram for each blow. As a result, the operator can set automatically the number and intensity of blows in each die cavity. Electronic blow control increases the efficiency of the hammer operations and decreases the noise and vibration associated with unnecessarily strong hammer blows.

Power-Drop Hammers

In a power-drop hammer, the ram is accelerated during the downstroke by air, steam, or hydraulic pressure. This equipment is used almost exclusively for impression or closed-die forging.

The steam or air-powered drop hammer (Fig. 2) is the most powerful machine in general use for the production of impression-die forgings by impact pressure. A heavy anvil block supports two frame members that accurately guide a vertically moving ram; the frame also supports a cylinder that, through a piston and piston rod, motivates the ram. In its lower face, the ram carries an upper die, which contains one part of the impression that shapes the forging. The lower die, which contains the remainder of the impression, is keyed into an anvil cap firmly wedged in place on the anvil. The motion of the piston is controlled by a valve, which admits steam, air, or hydraulic oil to the upper or lower side of the piston. The valve usually is controlled electronically. Most modern power-drop hammers are equipped with programmable electronic blow control to adjust the intensity of each blow.



Safety-cushion head
Cylinder
Cylinder bushing
Piston
Tile plate
Rod-gland sleeve
Piston rod
Guide
Ram
Upper die
Lower die
Anvil
Anvil cap
Motion arm
Die
Safety-cushion piston
Motion-valve connection
Inlet pipe
Motion valve
Exhaust pipe
Throttle valve connection
Lever connection
Throttle-control unit
Treadle connection
Treadle board
Lubrication quill
Throttle valve
Frame
Guide bolt

Fig. 2 Principal components of a power-drop hammer with foot control to regulate the force of the blow

Power-drop hammers are rated by the weight of the striking mass, not including the upper die. Hammer ratings commonly range from approximately 450 to 32,000 kg (1000 to 70,000 lb). The striking velocity by the downward pressure on the piston sometimes exceeds 7.5 m/s (25 ft/s).

Rating of hammers by the weight of the striking mass is not correct, although it has been common practice. Realistically, hammers should be rated by the maximum energy, in joules or foot-pounds, that the ram can impart to the hot metal during a single blow at the maximum energy setting of the hammer controls. The useful energy supplied to the forged metal by the hammer ram depends on (a) the hammer design (weight of the ram and the pressure on the top of the piston), (b) the ratio of the anvil weight versus the ram weight, and (c) the hammer foundation design.

Power-drop hammers are suitable for the production of large forgings. (Forgings commonly produced in power-drop hammers range in weight from 50 lb to several tons.) An important advantage is that the striking intensity is entirely under the control of the operator or is preset by the electronic blow-control system. Consequently, auxiliary impressions in the dies can be used to preform the billet to a shape that will best fill the finishing impressions in the dies. This helps create proper grain flow, soundness, and less scrap, with minimum die wear. When adequate preliminary impressions cannot be incorporated in the same set of die blocks, two or more hammers are used to produce adequate shaping or blocking to an intermediate shape before the final die is used.

The greater striking forces developed with power-drop hammers give rise to several disadvantages. As much as 15 to 25% (and, in hard finishing blows, up to 80%) of the kinetic energy of the ram is dissipated in the anvil block and foundation, and therefore does not contribute to deformation of the workpiece. This loss of energy is most critical when finishing blows are struck and the actual deformation per stroke is relatively slight. The transmitted energy imposes a high stress on the anvil block and can even break it. The transmitted energy also develops violent, and potentially damaging, shocks in the surrounding floor area. This necessitates the need for shock absorbing materials, such as timber or iron felt, in anvil-block foundations, adding appreciably to foundation cost.

Die-Forger Hammers. Similar in operation to power-drop hammers, die-forger hammers have a shorter stroke and faster striking rate. Typically, these hammers can deliver approximately 5.5 to 90 kJ (4000 to 66,000 ft · lb) of energy per blow. Pressurized air energizes the blow.

Counterblow Hammers. Another variation of the power-drop hammer, the counterblow hammer develops striking force by the movement of two rams, simultaneously approaching from opposite directions and meeting at a midway point. Some hammers are air or hydraulically actuated; others incorporate a combination of mechanical-hydraulic, steam-hydraulic, air-hydraulic, or mechanical-air activation.

In the steam-hydraulic actuating system (Fig. 3) steam is admitted to the upper cylinder and drives the upper ram downward. Simultaneously, pistons connected to the upper ram act through a hydraulic linkage to force the lower ram upward. Because the weight of the lower ram and piston assembly is greater than that of the upper assembly, the rams retract automatically after the blow. Retraction speed is increased by steam pressure acting upward on the piston. Through proper design relative to weights (including tooling and workpiece) and hydraulics (slower lower-assembly velocities), the kinetic energy of the upper and lower assemblies can be balanced at impact.

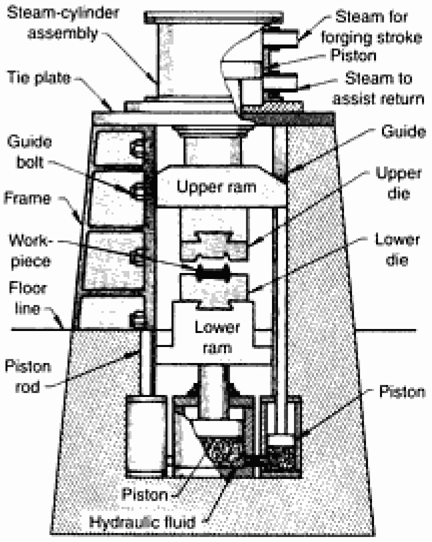


Fig. 3 Essential components of a vertical counterblow hammer with a steam-hydraulic actuating system

The rams of a counterblow hammer are capable of striking repeated blows; they develop combined velocities of 5 to 6 m/s (6 to 20 ft/s). Compared to single-action hammers, vibration of impact is reduced, and approximately the full energy of each blow is delivered to the workpiece, without loss to an anvil. As a result, the wear of moving hammer parts is minimized, contributing to longer operating life. At the time of impact, forces are canceled out, and no energy is lost to foundations. In fact the large inertia blocks and foundations of conventional power-drop hammers are not required.

A horizontal counterblow hammer has two opposing, die-carrying rams that are moved horizontally by compressed air. Heated stock is positioned automatically at each die impression by a present pattern of accurately timed movements of a stock-handling device. A 90° rotation of stock can be programmed between blows.

High-Energy-Rate Forging Machines

High-energy-rate forging (HERF) machines are high speed hammers. They can be grouped into three basic designs: ram-and-inner-frame, two-ram, and controlled-energy-flow. Each differs in engineering and operating features, but all are essentially very high-velocity, single-blow hammers that require less moving weight than conventional hammers to achieve the same impact energy per blow. All the designs use counterblow principles to minimize foundation requirements and energy losses. All the designs use inert high-pressure gas controlled by a quick release mechanism for rapid acceleration of the ram. The machine frame is not required to resist the forging forces in any of the designs.

Ram-and-Inner-Frame Machines. The frames for these machines (Fig. 4a) consist of two units: an inner or working frame connected to a firing chamber and an outer or guiding frame within which the inner frame is free to move vertically. As the trigger-gas seal opens, high-pressure gas from the firing chamber acts on the top face of the piston and forces the ram and upper die downward. Reaction to the downward acceleration of the ram raises the inner frame and lower die.

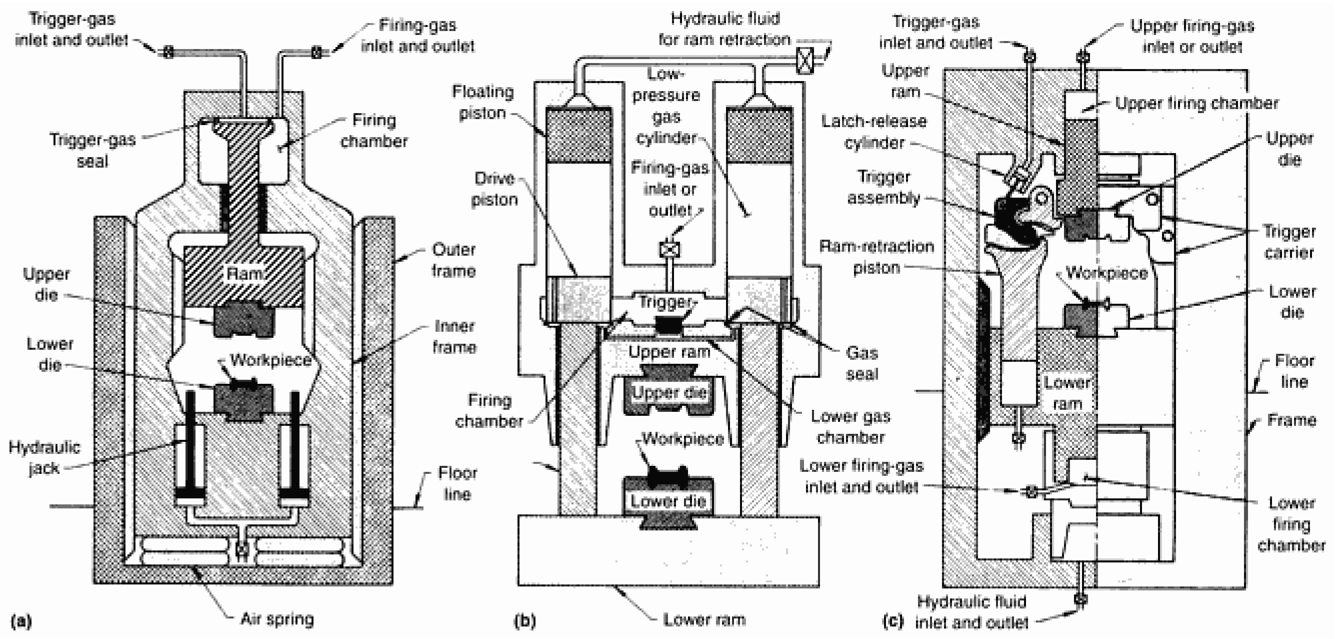

Trigger-gas inlet and outlet
Firing-gas inlet and outlet
Trigger-gas seal
Firing chamber
Ram
Outer frame
Upper die
Lower die
Workpiece
Inner frame
Hydraulic jack
Floor line
Air spring
(a)
Hydraulic fluid for ram retraction
Floating piston
Low-pressure gas cylinder
Drive piston
Firing-gas inlet or outlet
Trigger
Upper ram
Upper die
Workpiece
Lower die
Firing chamber
Gas seal
Lower gas chamber
Lower ram
(b)
Trigger-gas inlet and outlet
Upper firing-gas inlet or outlet
Upper ram
Upper firing chamber
Latch-release cylinder
Upper die
Trigger assembly
Trigger carrier
Ram-retraction piston
Workpiece
Lower die
Floor line
Lower ram
Frame
Lower firing-gas inlet and outlet
Lower firing chamber
Hydraulic fluid inlet and outlet
(c)

Fig. 4 Three types of machines for high-energy-rate forging. (a) Ram-and-inner-frame machine. (b) Two-ram machine. (c) Controlled-energy-flow machine. Triggering and expansion of gas in the firing chamber cause the upper and lower rams to move toward each other at high velocity. An outer frame provides close guiding surfaces for the rams. See text for descriptions of the mechanics of operation.

The machine is made ready for the next blow by hydraulic jacks that elevate the ram until the trigger-gas seal between the upper surface of the firing chamber and the ram piston is reestablished. Venting of the seal gas, and gas pressure on the lower lip of the piston, then hold the ram in the elevated position.

This type of machine is produced in several sizes, ranging in capacity from 17 to 745 kJ (12,500 to 550,000 ft · lb) of impact energy.

Two-Ram Machines. In a two-ram machine (Fig. 4b), the counterblow is achieved by means of an upper ram and a lower ram. An outer frame (not shown) guides the two rams vertically. Vertical movement of the trigger permits high-pressure gas to enter the lower chamber and the space beneath the drive piston. This forces the drive piston, rod, lower ram, and lower die upward. The reaction to this force drives the floating piston, cylinder, upper ram, and upper die downward. The rods provide relative guidance between the moving upper and lower assemblies.

After the blow, hydraulic fluid enters the cylinder, returning the upper and lower rams to their starting positions. The gas is recompressed by the floating pistons, and the gas seals at the lower edges of the drive pistons are reestablished. When the trigger is closed, the hydraulic pressure is released, the high-pressure gas in the lower chamber expands through the drive-piston ports and forces the floating pistons up, and the machine is ready for the next blow. These machines are made in several sizes; the largest is rated at 407 kg (300,000 ft · lb) of impact energy.

Controlled-energy-flow forging machines (Fig. 4c) are counterblow machines with separately adjustable gas cylinders and separate rams for the upper and lower dies; however, they do not rely on self reacting principles. The lower ram has a hydraulically actuated vertical adjustment cylinder so that various stroke lengths can be preset.

The trigger, although pneumatically operated, is a massive mechanical latch that returns and holds the rams through mechanical support of the upper ram and hydraulic connection with the lower ram. This arrangement assures simultaneous release of the two rams. Controlled-energy-flow forging machines have been made in two sizes, with ratings of 99 and 542 kJ (73,000 and 400,000 ft · lb) of maximum impact energy.

Applicability. High-energy-rate forging machines basically are limited to fully symmetrical or concentric forgings such as wheels and gears or for coining applications where little metal movement but high die forces are required. The practical use of these machines has been limited and is expected to remain so. Parts that can be forged in high-energy-rate forging machines also can be forged in counterblow hammers or mechanical presses. High-velocity impact during the forging blow reduces die life and increases machine maintenance requirements. Therefore, lower-intensity-stroke machines, for example, hammers and presses, are more economical to use in most applications. Cases where the extremely high-forging rate imparts unusual properties and microstructures to the forged materials may be exceptions.

Open-Die Forging Hammers

Open-die forging hammers, commonly known as general forging hammers, are used to make a large percentage of open-die forgings. In size, they range from small hammers rated at approximately 11 to 23 kg (25 to 50 lb) to hammers with ratings as high as 11,000 kg (24,000 lb). A general forging hammer is operated by steam or compressed air, usually at pressures of 690 to 825 kPa (100 to 120 psi) for steam and 620 to 690 kPa (90 to 100 psi) for compressed air. These conditions are similar to those of the power-drop hammer used for closed-die forging.

Smaller hammers--those rated at less than approximately 455 kg (1000 lb)--are usually found in repair or maintenance departments of manufacturing plants, where they are used to forge repair parts, to dress tools, and to shape many items needed by maintenance departments. These small hammers are not considered part of a forge shop.

There are two basic differences between power-drop hammers used for closed-die forging and those used for open-die forging. First, a modern power-drop hammer has blow-energy control to assist the operator in setting the intensity of each blow. In hammers for closed-die forging, the hammer stroke is limited by the upper die surface contacting the surface of the lower die face. In open-die forging, the upper and lower dies do not make contact; stroke-position control is provided through control of the air or steam valve that actuates the hammer piston.

The second difference between closed-die and open-die forging hammers is that the anvil of an open-die hammer is separate and independent of the hammer frame that contains the striking ram and the top die. Separation of the anvil from the frame allows the anvil to give way under a heavy blow or series of blows, without disturbing the frame. The anvil can rest on oak timbers, which absorb the hammering shock.

Open-die hammers are made either with a single frame (often termed C-frame or single-arch hammers) or with a double frame (often called double-arch hammers). Double-frame general forging hammers (Fig. 5) usually come in rated sizes from 2720 to 10,900 kg (6000 to 24,000 lb), although larger hammers have been built.

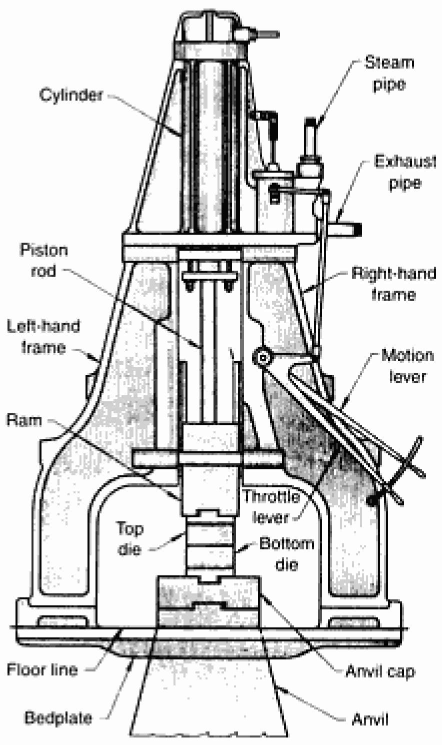


Fig. 5 Double-frame power hammer used for open-die forging

Mechanical Presses

A massive, rotating flywheel imparts the energy to drive the ram into the workpiece in a mechanical press. Driven by a motor and controlled by an air clutch, a full-eccentric drive shaft provides a constant-length stroke to a vertically operating ram. The ram carries the top (or moving) die, whereas the bottom (or stationary) die is clamped to the die seat of the main frame. The ram stroke is shorter than that of a forging hammer or a hydraulic press. Ram speed is greatest at the center of the stroke, but force is greatest at the bottom of the stroke.

Because of the short stroke, mechanical presses are best suited for low profile forgings. Capacities of these forging presses are rated on the maximum force they can apply and range from approximately 3 to 140 MN (300 to 16,000 tonf).

Knuckle-joint mechanical presses are operated by an eccentric shaft or by a crankshaft. The knuckle mechanism increases available forging force but reduces ram-stroke length. Thus, knuckle-joint presses are used primarily for flash trimming, coining, or sizing.

Mechanical forging presses are similar to eccentric-shaft, straight-side, single-action presses used for forming sheet metal. In detail, however, mechanical forging presses are considerably different from mechanical presses that are used for forming sheet. Forging presses are built stronger than presses for forming sheet metal. Forging presses deliver their maximum force within 3.2 mm ($\frac{1}{8}$ in.) of the end of the stroke because maximum pressure is required to form the flash. In addition, the slide velocity in a forging press is faster than that of a sheet-metal deep drawing press.

The character of the blow in a forging press resembles that of an upsetting machine, thus combining some features of hammers and upsetters. Mechanical forging presses use drive mechanisms similar to those of upsetters, although an upsetter generally is a horizontal machine.

Mechanical forging presses provide higher production rates than forging hammers. Stroking rates vary from approximately 30 strokes per minute, for a 140 MN (16,000 tonf) press, to approximately 100 strokes per minute, for a 4500 kN (500 tonf) press. Because the impact is less in presses than in hammers, dies can be less massive, thus requiring less tool steel to make the dies. Cast dies can be used. Also because presses deliver a less severe impact blow, dies can be operated at higher hardness, which prolongs die life. In addition, presses generate less noise and vibration than hammers. Presses require less operator skill than is required for hammers, they are easier to automate, and they can produce more precise parts.

However, initial cost of mechanical forging presses is up to three times the cost of a hammer to produce the same forging. A press delivers consecutive strokes of equal force and therefore, is less suitable for preliminary shaping operations such as fullering or rollering.

Hydraulic Presses

Hydraulic presses (Fig. 6) are used for both open-die and impression-die (closed-die) forging. The ram is driven by hydraulic cylinders and pistons, which are part of a high-pressure hydraulic or hydropneumatic system. Because pressing speeds can be controlled accurately, these presses are advantageous for producing close-tolerance, precision forgings.

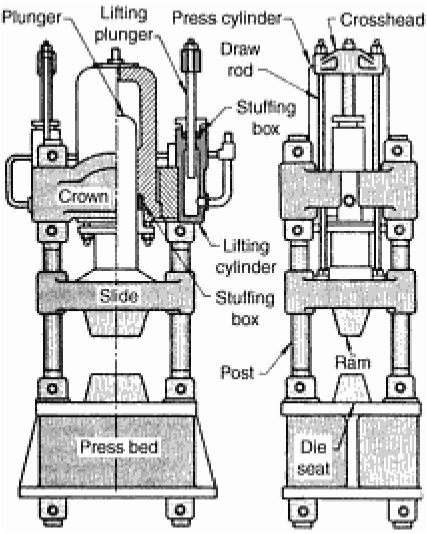


Fig. 6 Components of a four-post hydraulic press for closed-die forging

For precision forging, presses can be equipped with a hydraulic control circuit that produces a rapid advance stroke, followed by preselected first and second pressing speeds. Many other process variables can be controlled including pullout speed, force, dwell times, and ejection.

Hydraulic presses are equipped with either direct drives or accumulator drives. Direct-driven presses use a hydraulic pump to feed oil under pressure into the cylinder of the press continuously during the stroke. Thus, the pump capacity determines the maximum available press speed and press load. In accumulator-driven presses, a water emulsion, the working medium, is stored in an accumulator under nitrogen pressure. When the press stroke is initiated, the pressurized water emulsion is fed into the press cylinder. During the press stroke, the water emulsion expands and loses some of its initial pressure. In automatic programmed forging operations, direct drive offers the advantage of very close control of ram speed and ram position.

Capacities of hydraulic presses range from 1.8 to 125 MN (200 to 14,000 tonf) for open-die presses and 4.5 to 640 MN (500 to 72,000 tonf) for impression-die presses.

With hydraulic presses, pressure can be changed at any point in the stroke by adjusting the pressure control valve. Rates of deformation can be controlled and varied during the stroke, if required. This is especially important in forging of metals that rupture if subjected to high deformation rates. Parts can be forged using split dies to create offset flanges, projections, back draft, and other design features that are extremely difficult, if not impossible, to incorporate in hammer forgings.

When excessive heat transfer (from the hot workpiece to the dies) is not a problem, or can be eliminated, the gentle squeezing action of a hydraulic press results in lower maintenance cost and increased die life because of less shock compared with other types of forging equipment. Maximum press load can be limited to protect the tooling.

One disadvantage of a hydraulic press is that the initial cost is higher than that of a mechanical press of equivalent capacity. In addition, the action of a hydraulic press is slower than that of a mechanical press. The slower action produces longer contact between the dies and the workpiece, which allows time for heat transfer from the hot workpiece to the dies. This reduces die life, particularly when forging high-temperature materials such as steel, titanium, and nickel alloys.

Screw Presses

Machines in this category use energy from a flywheel to turn a screw that drives the ram. Screw presses are used for precision-forging, steam-turbine, and jet-engine compressor blades; diesel-engine crankshafts; and gearlike parts. The process, when economical, can be used for open- and impression-die forging and precision forging of brass and aluminum parts.

Drive Systems

The screw press uses a friction, gear, electric, or hydraulic drive to accelerate the flywheel and the screw assembly, and it converts the angular kinetic energy into the linear energy of the slide or ram (Fig. 7).

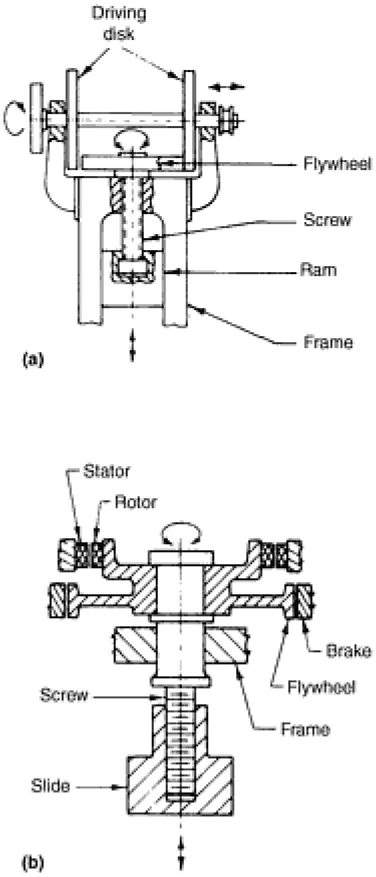


Fig. 7 Two basic designs of screw presses. (a) Friction-drive press. (b) Direct-electric-drive press

In the friction-drive press (Fig. 7a), the driving disks, mounted on a horizontal shaft, are rotated continuously. For a downstroke, one of the driving disks is pressed against the flywheel by a servomotor. The flywheel, which is connected to the screw either positively or by a friction slip clutch, is accelerated by this driving disk through friction. The flywheel energy and the ram speed continue to increase until the ram hits the workpiece. Thus, the forming load is built up and transmitted through the slide, the screw, and the bed to the press frame. When the entire energy in the flywheel is used in deforming the workpiece and elastically deflecting the press, the flywheel, the screw, and the slide stop. At this moment, the servomotor activates the horizontal shaft and presses the upstroke driving disk wheel against the flywheel. Thus, the flywheel and the screw are accelerated in the reverse direction, and the slide is lifted to its top position.

In the direct-electric-drive press (Fig. 7b), a reversible electric motor is built directly on the screw and on the frame, above the flywheel. The screw is threaded into the ram or slide and does not move vertically. To reverse the direction of flywheel rotation, the electric motor is reversed after each downstroke and upstroke.

Other Drive Systems. In addition to friction and direct-electric drives, several other types of mechanical, electric, and hydraulic drives are commonly used in screw presses. A relatively new screw press drive (Fig. 8) uses a flywheel similar to that used to initiate the stroke of an eccentric mechanical forging press. Upon engagement of the clutch, the screw is accelerated rapidly and reaches the speed of the flywheel. As a result, the ram moves downward. The downstroke charges a hydropneumatic lift cylinder system. The downstroke is terminated in either of two ways: by controlling the ram position with a position switch, or by controlling the maximum load on the ram by disengaging the clutch and the flywheel from the screw when the preset forming load is reached. The ram is then lifted by the lift-up cylinders, releasing the elastic energy stored in the press frame, the screw, and the lift-up cylinders. At the end of the upstroke, the ram is stopped and held in position by a hydraulic brake.

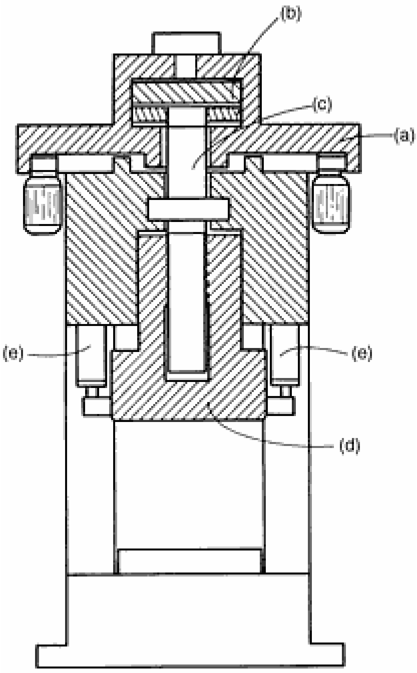


Fig. 8 Screw press drive combining the characteristics of mechanical and screw presses. (a) Flywheel. (b) Air-operated clutch. (c) Screw. (d) Ram. (e) Lift-up cylinders

This press provides a high and nearly constant ram speed throughout the stroke with full press load at any position of the stroke. Other advantages include high deformation energy, overload protection, and short contact time between the workpiece and the tools.

This drive system is limited in that only two levels of energy are available, high and low. Furthermore, because force is controlled through slippage of the clutch, application of power is not predictable. The large amount of energy available can create material flow problems.

Capacities and Speed

Screw presses usually are rated by the diameter of the screw. Screw diameters range from 100 to 635 mm (4 to 25 in.). These sizes translate to nominal forces of 1.4 to 35.6 MN (160 to 4000 tonf). Direct electric-drive screw presses have been built with 600 mm (24 in.) diameter screws, or 37.3 MN (4190 tonf) of nominal force capacity. Hydraulically driven screw presses have hard-on-hard blow capacities up to 310 MN (35,000 tonf).

Press speed in strokes per minute depends largely on the energy required by the specific forming process and on the capacity of the drive mechanism to accelerate the screw and the flywheel. In general, however, the production rate of a screw press is lower than that of a mechanical press, especially in automated high-volume operations. Small screw presses operate up to 40 to 50 strokes per minute, while larger presses operate at approximately 12 to 16 strokes per minute.

Multiple-Ram Presses

Hollow, flashless forgings for valve bodies, hydraulic cylinders, seamless tubes, and a variety of pressure vessels can be produced in a hydraulic press with multiple rams. The rams converge on the workpiece in vertical and horizontal planes, alternately or in combination, and fill the die by displacement of metal outward from a central cavity developed by one or more of the punches (Fig. 9).

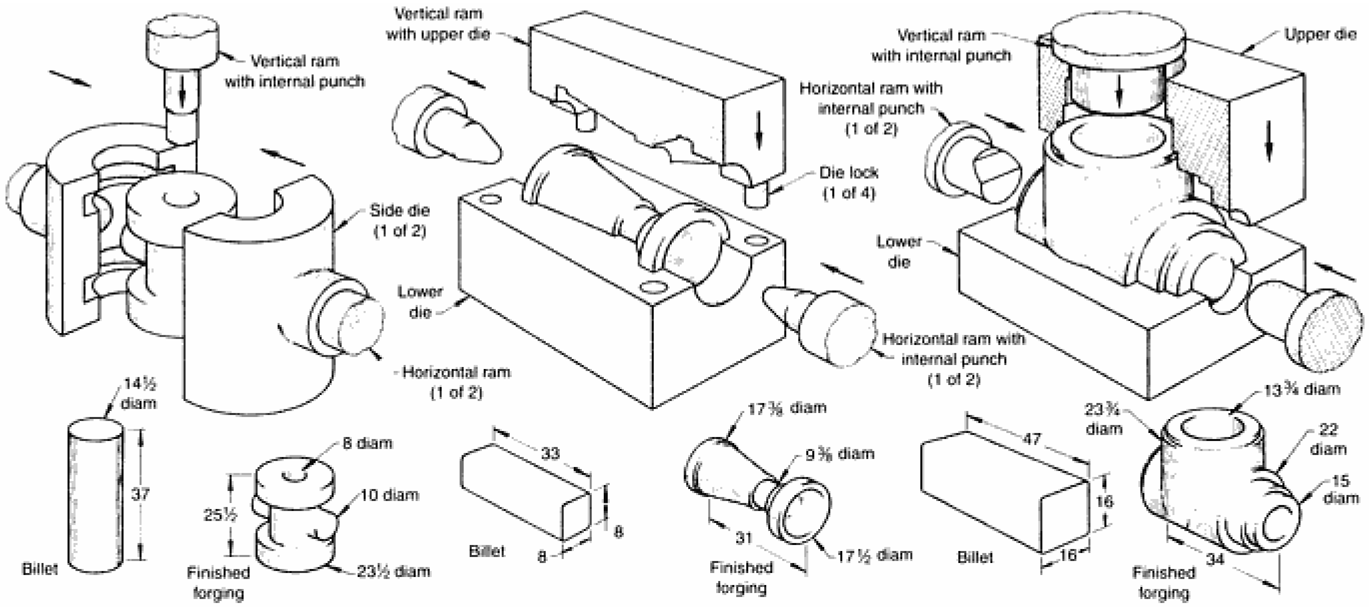

Vertical ram with internal punch
Side die (1 of 2)
Horizontal ram (1 of 2)
14½ diam
37
Billet
8 diam
10 diam
25½
23½ diam
Finished forging
Vertical ram with upper die
Lower die
33
8
8
Billet
Die lock (1 of 4)
Horizontal ram with internal punch (1 of 2)
17⅜ diam
9⅜ diam
31
17½ diam
Finished forging
Vertical ram with internal punch
Upper die
Horizontal ram with internal punch (1 of 2)
Lower die
47
16
16
Billet
23¾ diam
13¾ diam
22 diam
15 diam
34
Finished forging

Fig. 9 Examples of multiple-ram forgings. Displacement of metal can take place from vertical, horizontal, and combined vertical and horizontal planes. Dimensions given in inches.

Piercing holes in a forging at an angle to the normal direction of forging force can save considerable material and machining time required to generate the holes. In addition to versatility provided by multiple rams, these presses can be used for forward or reverse extrusion. Lack of flash at the parting line decreases stress-corrosion cracking in forging alloys susceptible to this type of failure. Multidirectional hot working, characteristic of this process, decreases adverse directional effects on mechanical properties.

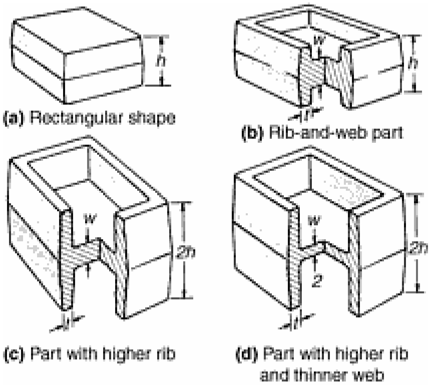
Die Design and Materials

THE TECHNOLOGY in this section applies in general to the design of dies, terminology, and materials selection for dies for the most common hot-forging processes--particularly those using vertical presses, hammers, and horizontal forging machines (upsetters). More specific details are given in the next section, which discusses each of the primary forging processes.

Designing Parts for Forging

Metal flow in forging is greatly influenced by part or die geometry. Often, several operations (preforming or blocking) are needed to achieve gradual flow of the metal from an initially simple shape (cylinder or round-cornered, square billet) into the more complex shape of the final forging. Generally, spherical and blocklike shapes are the easiest to forge in impression or closed dies. Parts with long, thin sections or projections (webs and ribs) are more difficult to forge because they have more surface area per unit volume. The shape of the final forging determines process variables including friction, temperature changes in the dies, and pressure required to fill the die cavities. The surface-to-volume ratio of a forging is directly related to the difficulty of producing the forging.

The ease of forging complex shapes depends on the relative proportions of vertical and horizontal projections on the part. For example, parts (c) and (d) in Fig. 10 require not only higher forging loads, but also at least one more forging operation than parts (a) and (b) to ensure die filling.



(a) Rectangular shape

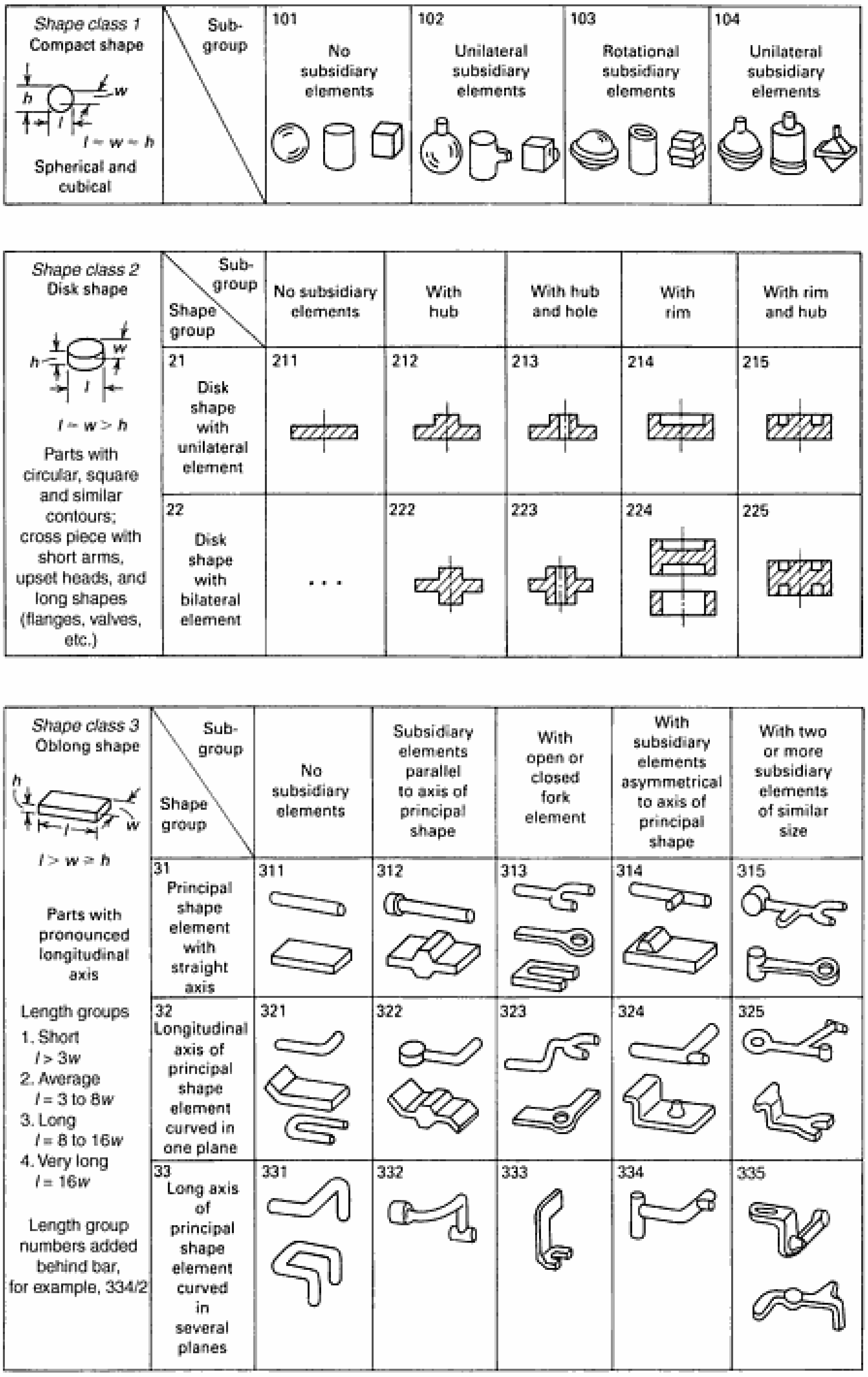
(b) Rib-and-web part

(c) Part with higher rib

(d) Part with higher rib and thinner web

Fig. 10 Rectangular shape and three modifications, showing increasing forging difficulty (from a to d) with increasing rib height and decreasing web thickness

Most forgings can be classified into three main groups (Fig. 11). For the first group, the so-called "compact shapes," the three major dimensions (length, *l*; width, *w*; and height, *h*) are approximately equal. Few parts fall into this group. In the second group, "disk shapes," two of the three dimensions (length, *l*, and width, *w*) are approximately equal and greater than the height, *h*. All round forgings belong to this group, which includes approximately 30% of all commonly used forgings. The third group consists of long shapes for which one major dimension is significantly greater than the other two ($l > w \geq h$). These three basic groups are further divided into subgroups depending on the presence and type of elements subsidiary to the basic shape.



Shape class 1 Compact shape $l \approx w \approx h$ Spherical and cubical	Sub-group	101 No subsidiary elements	102 Unilateral subsidiary elements	103 Rotational subsidiary elements	104 Unilateral subsidiary elements

Shape class 2 Disk shape	Sub-group Shape group	No subsidiary elements	With hub	With hub and hole	With rim	With rim and hub
$l \approx w > h$ Parts with circular, square and similar contours; cross piece with short arms, upset heads, and long shapes (flanges, valves, etc.)	21 Disk shape with unilateral element	211	212	213	214	215
	22 Disk shape with bilateral element	. . .	222	223	224	225

Shape class 3 Oblong shape	Sub-group Shape group	No subsidiary elements	Subsidiary elements parallel to axis of principal shape	With open or closed fork element	With subsidiary elements asymmetrical to axis of principal shape	With two or more subsidiary elements of similar size
$l > w \geq h$ Parts with pronounced longitudinal axis	31 Principal shape element with straight axis	311	312	313	314	315
Length groups 1. Short $l > 3w$ 2. Average $l = 3$ to $8w$ 3. Long $l = 8$ to $16w$ 4. Very long $l = 16w$	32 Longitudinal axis of principal shape element curved in one plane	321	322	323	324	325
Length group numbers added behind bar, for example, 334/2	33 Long axis of principal shape element curved in several planes	331	332	333	334	335

Fig. 11 Classification of forging shapes

This "shape classification" can be useful for estimating costs and predicting preforming steps. However, this method is not entirely quantitative and requires subjective evaluation based on past experience.

Parting Line

The parting line is the line along the forging at which the dies meet. It can be in a single plane, curved, or irregular. The shape and location of the parting line determine die cost, draft requirements, grain flow, and trimming procedures.

In most forgings, the parting line is at the largest cross section of the part because it is easier to spread metal by forging action than to force it into deep die impressions. If the largest cross section coincides with a flat side of a forging, the parting line could be located along the edges of the flat section, thus placing the entire impression in one die half. This reduces die costs because one die is simply a flat surface. This also prevents mismatch between upper and lower dies and allows forging flash to be trimmed readily.

When a die set with one flat die cannot be used, the parting line should be positioned to provide for location of the preform in the finished impression of the forging die and the finished forging in the trimming die.

Because part of the metal flow is toward the parting line during forging, the location of the parting line affects the grain-flow characteristics of a forged piece. For good internal-flow patterns in, for example, a forging having a vertical wall adjacent to a bottom web section, a parting line on the outer side of the wall should be either adjacent to the web section and near the bottom of the wall, or at the top of the wall. A parting line at any point above the center of the bottom web but below the top of the wall can disrupt the grain flow and cause defects in the forging.

Because the dies move only in a straight line, and because the forging must be removed from the die without damage either to the impression or to the forging, die impressions usually can have no undercuts. Frequently, the forging can be inclined with respect to the forging plane to overcome the effect of an undercut. In press forging, "split dies," confined in a holder during forging and opened up for removal of the forged part, allow forging parts with undercuts and complex shapes.

Locks and Counterlocks

Many forgings require a parting line that is not flat and, correspondingly, die parting surfaces that are neither planar nor perpendicular to the direction of the forging force. Dies that have a change in the plane of their mating surfaces, and that, therefore, mesh ("lock") in a vertical direction when closed, are called locked dies.

In forging with locked dies, side or end thrust is frequently a problem. A strong lateral thrust during forging can cause mismatch of the dies or breakage of the forging equipment.

To eliminate or control side thrust, forgings can be inclined, rotated, or otherwise placed in the dies to balance the lateral forces (Fig. 12c). Flash can be used to cushion the shock and help absorb the lateral forces. For large production quantities of parts small enough to be forged in multiple-part dies, the impressions can be arranged so the side thrusts cancel each other.

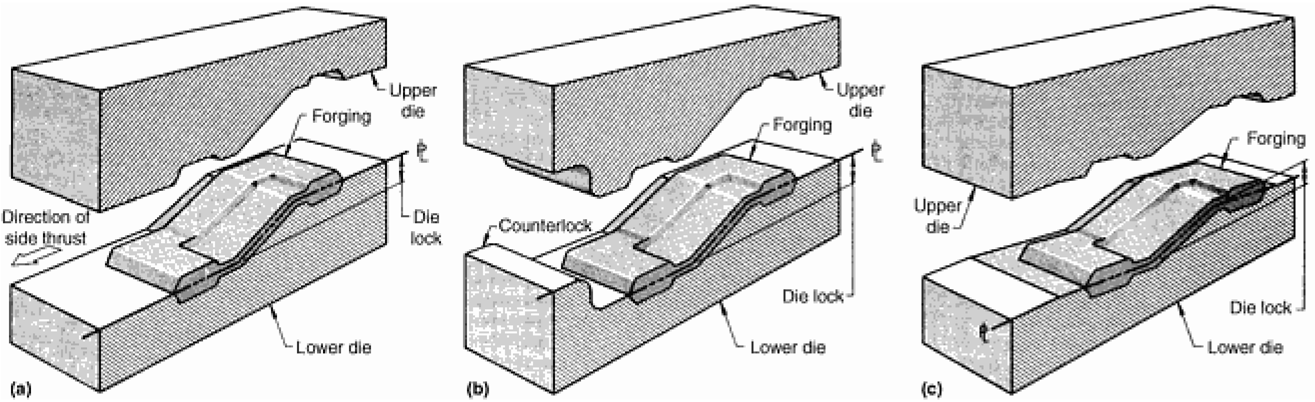


Fig. 12 Locked and counterlocked dies. Locked dies (a) with no means of counteracting side thrust, (b) with counterlock, and (c) requiring no counterlock because the forging has been rotated to minimize side thrust.

Generally, alignment between the upper and lower die impressions can be maintained with proper placement of the impression in the die, using clearance between the guides on the hammer or press to absorb side thrust. When these techniques will not work, side thrust can be counteracted by machining mating projections and recesses, or counterlocks, into the parting surfaces of the dies.

Counterlocks can be relatively simple. A pin lock, consisting of a round or square peglike section with its mating section, may be all that is required to control mismatch. Two such sections, or sections at each corner of the die, may be necessary. A simple raised section with a mating countersunk section running the width and the length of the die can control side and end match. Counterlocks of these types should not be used in long production runs.

Counterlocks in high-production dies should be carefully designed and constructed. The height of the counterlock usually is equal to, or slightly greater than, the depth of the locking portion of the die. The thickness of the counterlock should be at least 1.5 times the height to provide adequate strength to resist side thrust. Adequate lubrication of the sliding surfaces is difficult to maintain because of the temperature of the die and the heat radiated from the workpiece. Therefore, the surfaces of the counterlock wear rapidly and need frequent reworking. Because of the cost of constructing and maintaining counterlocks, they should be used only if a forging cannot be produced more economically without them.

Size of the Die Block

The size of the die block is determined by the width of the finished "platter," including allowance for flash and gutters and allowance for the preforming impressions and for sprues and gates for the blocker and finisher impressions. ("Platter" is defined as the entire workpiece on which the forging equipment performs work, including the flash, sprue, tonghold, and as many forgings as are made at one time.)

The impressions in a block should be spaced in such a way that the size of the die face is suitable for the size of the hammer, that flash cannot flow from one impression to another, and that the forging is not pinched in preform impressions that are too narrow. Die pressures vary with different work metals and workpiece shapes. A larger die block usually is needed as die pressure is increased.

When standard forged alloy steel rams are used in gravity-drop hammers, the minimum area of the upper die face recommended by one manufacturer is 30% of the ram area for 225 to 1135 kg (500 to 2500 lb) hammers, 35% for 1360 to 2270 kg (3000 to 5000 lb) hammers and 40% for hammers with capacities of 2720 kg (6000 lb) or more. The weight of the upper die should be 25 to 30% of the falling weight. Heavier dies are not recommended for regular practice. For power-drop hammers, the area of the die face should be 50% of the ram area for 455 to 1360 kg (1000 to 3000 lb) hammers, 60% for 1815 to 3630 kg (4000 to 8000 lb) hammers and 70% for hammers with capacities of 4535 kg (10,000 lb) or more.

The minimum shut height of the dies should be at least 50 mm (2 in.) greater than the shut height of the hammer or press. The height of the die block determines the maximum impression depth because adequate die material must remain between the bottom of the impression and the bottom face of the die block to provide strength to the die.

Relatively small "die inserts" usually are used in mechanical presses. This saves expensive die material and the machining required on large die blocks. The dies are set in recesses in holders fastened to the ram and bed of the press. The dies are held in the recesses by clamps, and screws extending through the holders into the recesses provide for adjustment of die position and hold the die in position.

In modern press-forging operations, quick die-change mechanisms are available. Thus, die inserts can be held by hydraulic clamps that hold or release very quickly. Another method is to set up the inserts in an extra die holder outside the press and to change the entire die holder before starting a new production run.

Draft

Draft, or taper, is added to straight sidewalls of a forging to permit easier removal from the die impression. Forgings having round or oval cross sections or slanted sidewalls form their own draft. Forgings having straight sidewalls, such as square or rectangular sections, can be forged by parting them across the diagonal and tilting the impression in the die so that the parting line is parallel to the forging plane. Another method is to place the parting line at an angle to the forging plane and to machine a straight-wall cavity and a counterlock in each die.

The draft used in die impressions normally varies from 3 to 7° for external walls of the forged surfaces that surround holes or recesses having angles ranging from 5 to 10°. More draft is used on walls surrounding recesses to prevent forging sticking in the die as a result of natural shrinkage of the metal as it cools.

Flash Allowance

Flash, or excess metal extruded from the finisher impression during forging, acts as a cushion for impact blows and as a pressure-relief valve for the almost incompressible work metal. Also, it restricts the outward flow of the metal so that thin ribs and bosses can be filled in the upper die. The finisher impression generally includes a provision for flash. Figure 13 shows a typical arrangement (flash clearance, flash land, and gutter).

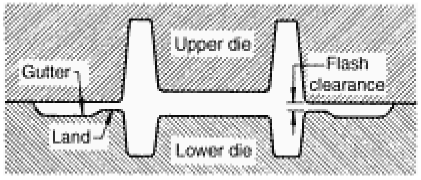


Fig. 13 Section through a forging, die finisher impression showing flash clearance, flash land, and gutter

A small amount of flash clearance in the dies, with an excess volume of work metal in the impression, requires much greater forging load or extra hammer blows to bring the forging to size. This creates excessive wear on the flash land, produces extreme pressures within the impression, and can cause dies to break.

Conversely, if the flash clearance is too great, work metal needed to fill the impression flows out through the flash land, and the forging is not properly filled. A balanced condition is needed, with just enough volume of metal to ensure that the flash clearance provided will force the work metal to fill the impression properly without causing excess wear and pressure.

The volume, the complexity, and the height-to-weight ratio of the forging, as well as the type of work metal, have an effect on flash thickness. General practice has been to use smaller flash clearance for small forgings than for large forgings. The amount of clearance varies from a minimum of approximately 0.51 mm (0.020 in.) up to a maximum of approximately 9.52 mm (0.375 in.) for forgings weighing up to 90 kg (200 lb). Approximately 3% of the maximum forging thickness is a reasonable guide for flash clearance.

The amount of excess work metal extruded from the impression can be too great to permit complete closing of the dies. To ensure complete closing, a gutter is provided for the excess metal after it has passed through the flash land.

Locating Impressions

The preform and finisher impressions should be positioned across the die block so the forging force is as near the center of the striking force (ram) as possible. This will minimize tipping of the ram, reduce wear on the ram guides, and help to maintain the thickness dimensions of the forging. When the forging is transferred manually to each impression, the impression for the operation requiring the greatest forging force (usually, the finisher) is placed at the center of the die block, and the remaining impressions are distributed as nearly equally as possible on each side of the die block.

Symmetrical forgings usually have their centerline along the front-to-back centerline of the die block. For asymmetrical forgings, the center of gravity can be used as a reference for positioning the preform and finisher impressions in the die block.

The center of gravity of a forging does not necessarily correspond to the center of the forging force because of the influence of thin sections on the forging force. Because the increase in force is not always directly proportional to the decrease in thickness, both the flash and the location of the thin sections must be considered when locating the impressions in a die block. Evenly distributed flash has little effect on an out-of-balance condition; very thin sections have a marked effect. Often it is necessary to make some calculations in order to determine the center of loading of the finisher impression.

Die Inserts

Die inserts are used for economy in production of some forgings. In general, they prolong the life of the die block into which they fit. Inserts can decrease production costs when several can be made for the cost of producing one solid die. The time required for changeover or replacement of inserts is brief because a second set of inserts can be made while the first set is being used. Finally, more forgings can be made accurately in a die with inserts than in a solid die because steel of higher alloy content and greater hardness can be used in inserts than would be safe or economical to use in solid dies.

Some commercial drop-hammer forge shops rarely use die inserts. However, nearly all press shops use die inserts.

Inserts can contain the impression of only the portion of a forging subjected to greatest wear, or they can contain the impression of a whole forging. An example of the first type of insert is the plug-type insert used for forging deep cavities. Examples of the second type include master-block inserts that permit forging of a variety of shallow parts in a single die block and inserts for replacement of impressions that wear the most rapidly in multiple-impression dies.

A plug-type insert (Fig. 14) is usually a projection in the center of the die to forge a hub or cup, for example. In some impressions, the plug may not be in the center, and more than one plug can be used in a single impression. Although plugs are used in either shallow or deep impressions, the need is usually greater in deep impressions.

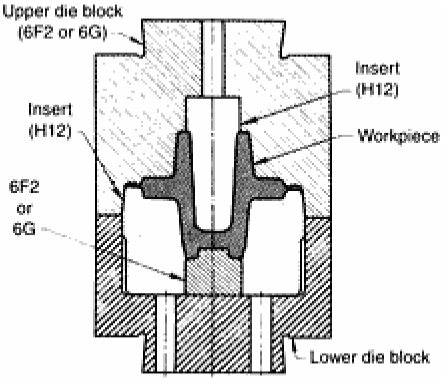


Fig. 14 Use of a plug-type insert in combination with a nearly complete insert in the lower die block for making a forging of extreme severity. For forging this workpiece (an automotive axle housing), shown in cross section, an H12 tool steel plug in the upper die block is used in combination with a nearly complete H12 insert in the lower die block.

Plug inserts can be made either from prehardened die steel at a higher hardness than the main part of the die or, for longer life, from one of the hot-work tool steels. For extremely high wear resistance, the plug can be hardfaced.

Full inserts are generally used for shallow forgings. The insert can be of high hardness with less danger of breakage because it has the softer block as a backing. With only the insert made from a higher alloy steel, die costs are low. Changes in die designs are less costly when inserts are used; also, the same die block, or master block, can be used for slightly different forgings by changing inserts (Fig. 15a).

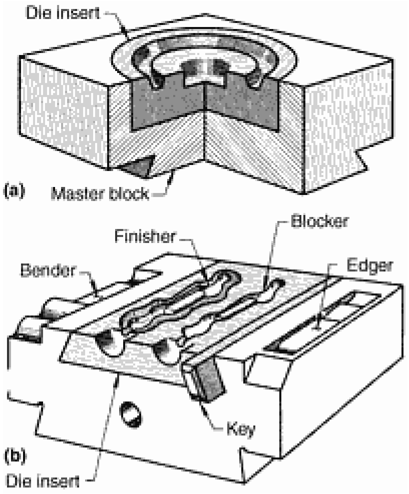


Fig. 15 Two types of die inserts used in hammer forging. (a) Full insert and master block for use in forging of gear blanks in hammers. (b) Multiple-impression insert for use when wear is excessive on one or more impressions. Such an insert is usually secured by a key.

Another application for an insert is in multiple-impression dies in which the impressions wear at different rates. Inserts are used for only the impressions that wear most rapidly. In the multiple-impression die, Fig. 15(b), the blocker and finisher impressions are in the same insert.

This technique is not necessarily limited to shallow impressions. If the insert contains a single impression, the impression can be of any practical depth. However, if it contains several impressions, the impression depth is limited to approximately 64 mm ($2\frac{1}{2}$ in.) or less. Width of the insert must be considered; sufficient wall thickness must be allowed between the edge of the impression and the edge of the insert so the die-block walls are not weakened too greatly.

Die Steels

Prehardened and tempered tool steel die blocks are available in a range of compositions and hardnesses. Tool steels are also available for small die blocks, die inserts, and trimming tools. Prehardened die-block steels are usually purchased on a basis of hardness.

Hot-work die steels are commonly used for hot-forging dies subjected to temperatures ranging from 315 to 650 °C (600 to 1200 °F). These materials contain chromium, tungsten, and in some cases vanadium or molybdenum or both. These alloying elements induce deep hardening characteristics and resistance to abrasion and softening. These steels are usually hardened by quenching in air or molten salt baths. The chromium-base steels (Table 2) contain approximately 5% Cr. High molybdenum content gives these materials resistance to softening; vanadium increases resistance to abrasion and softening. Tungsten improves toughness and hot hardness; tungsten-containing steels, however, are not resistant to thermal shock and cannot be cooled intermittently with water. The tungsten-base, hot-work die steels contain 9 to 18% W, 2 to 12% Cr, and sometimes small amounts of vanadium. The high tungsten content provides resistance to softening at high temperatures while maintaining adequate toughness, but it also makes water cooling of these steels impossible. Low-alloy proprietary steels are also used frequently as die materials for hot forging. Steels with ASM designations 6G, 6F2, and 6F3 have good toughness and shock resistance with good resistance to abrasion and heat checking. These steels are tempered at lower temperatures (usually 450 to 500 °C, or 840 to 930 °F); therefore, they are more suited for applications that do not result in high die surface temperatures (for example, die holders for hot forging or hammer die blocks).

Table 2 Compositions of tool and die materials for hot forging

Designation	Nominal composition, %								
	C	**Mn**	**Si**	**Co**	**Cr**	**Mo**	**Ni**	**V**	**W**
Chromium-base AISI hot-work tool steels									
H10	0.40	0.40	1.00	. . .	3.30	2.50	. . .	0.50	. . .
H11	0.35	0.30	1.00	. . .	5.00	1.50	. . .	0.40	. . .
H12	0.35	0.40	1.00	. . .	5.00	1.50	. . .	0.50	1.50
H13	0.38	0.30	1.00	. . .	5.25	1.50	. . .	1.00	. . .
H14	0.40	0.35	1.00	. . .	5.00	. . .	. . .	. . .	5.00
H19	0.40	0.30	0.30	4.25	4.25	0.40	. . .	2.10	4.10
Tungsten-base AISI hot-work tool steels									
H21	0.30	0.30	0.30	. . .	3.50	. . .	. . .	0.45	9.25
H22	0.35	0.30	0.30	. . .	2.00	. . .	. . .	0.40	11.00
H23	0.30	0.30	0.30	. . .	12.00	. . .	. . .	1.00	12.00
H24	0.45	0.30	0.30	. . .	3.0	. . .	. . .	0.50	15.00
H25	0.25	0.30	0.30	. . .	4.0	. . .	. . .	0.50	15.00
H26	0.50	0.30	0.30	. . .	4.0	. . .	. . .	1.00	18.00
Low-alloy proprietary steels									
ASM 6G	0.55	0.80	0.25	. . .	1.00	0.45	. . .	0.10	. . .
ASM 6F2	0.55	0.75	0.25	. . .	1.00	0.30	1.00	0.10	. . .
ASM 6F3	0.55	0.60	0.85	. . .	1.00	0.75	1.80	0.10	. . .

Selection Factors. Die steels are selected according to their ability to harden uniformly, to resist the abrasive action of the hot metal during forging, to withstand high pressure and heavy shock loads, and to resist cracking and checking caused by heat. Process variables to consider when selecting a die steel include shape, size, and weight of the forging; the metal to be forged; forging temperature; production quantity; and the forging equipment to be used.

Further variables in die material selection are cost of the die steel; how the die will be machined (before or after hardening); and forging tolerances (including those specified for draft angles). Typically, the selection also will be determined by previous experience with similar applications and the availability of machining equipment.

Additional information on properties and selection of die steels can be found in the Section "Tool Steels" in this Volume. Another excellent information source for die material selection is the *Tool Materials, ASM Specialty Handbook,* 1995. This Volume provides material selection guidelines for individual forging (hot and cold) and forming operations.

Computer-Aided Design and Computer-Aided Manufacture of Forging Dies

Computer analysis is well suited to the design of forging dies. Three-dimensional computer models can simulate metal flow through the die cavities and assist in establishing the best die design. Computer-aided design (CAD) and computer-aided manufacture (CAM) techniques are increasingly used in the forging industry. Once the computer determines the detailed dimensions of the die, it can translate them into instructions for numerically controlled machining of the final tooling. Software designed for die design provides a database reference for draft angles, flash dimensioning, and even control of the forging operation.

Software now can perform analyses based on sections through the workpiece. The computer can be used to predict forging load, stress concentrations in the die, elastic deformation of the die material, and metal flow of the workpiece. With little effort, these variables can be observed for alternative designs. Flash dimensions can be selected, and initial estimates of blocker or preform sections can be evaluated.

Once the die is created on the computer to the designer's satisfaction, the software presents a geometric database to be used to write numerical control instructions for milling the die. More information on computer modeling for forging is available in *Forming and Forging,* Volume 14, *ASM Handbook* (see the Section "Computer-Aided Process Design for Bulk Forming," in this Volume).

Forging Processes

THIS SECTION reviews specific characteristics of the most common forging processes. Process limitations, advantages, and disadvantages are discussed.

Open-Die Forging

Open-die forging--sometimes known as hand, smith, hammer, and flat-die forging--is a process in which the metal workpiece is not confined by dies. The process is typically associated with large parts, although parts can weigh from a few pounds to 150 tons. Probably 80% of all parts forged in open dies weigh between 30 and 1000 lb each.

Open-die forging progressively works the starting stock into the final shape, most commonly between flat-faced dies. This process can be selected when the forging is too large to be produced in closed dies. All forgeable metals can be forged in open dies.

Shapes Produced

Highly skilled hammer and press operators, with the aid of various auxiliary tools, can produce relatively complex shapes in open dies. However, because forging of complex shapes is time consuming and expensive, such forgings are produced only under unusual circumstances.

Most open-die forgings are rounds, squares, rectangles, hexagons, and octagons forged from billet stock, either to develop mechanical properties that are superior to those of rolled bars or to provide these shapes in compositions for which the shapes are not readily available as rolled products. Hubs that have a small diameter adjacent to a large diameter can be produced in small quantities by open-die forging.

Open-die forging is used to produce spindles, pinion gears, and rotors that are shaft-like parts with their major or functional diameters either in the center or at one end with one or more smaller diameters extending from one or both sides of the major diameter in shaft-like extensions. Forged and pierced blanks, prior to conversion to rolled rings, are open-die forged. Various basic shapes can be developed between open dies with the aid of "loose" tooling.

Hammers and Presses

The principles of operation of hammers and presses are discussed in the Section, "Hammers and Presses for Forging." However, open-die forging requires control of the stroke, the position and the speed of the ram, to obtain acceptable precision and quality in the forged part. Therefore, in general, only air or oil-driven power hammers and hydraulic presses are suitable for open-die forging. Modern open-die forging installations use direct-driven hydraulic presses with pulldown frame design and with quick die-changing mechanisms. In this type of press, the cylinder crosshead, which is located below floor level, is rigidly connected to the press columns. This assembly is movable and well guided. The center of gravity of this press is low, with high stiffness.

Direct-driven hydraulic presses offer better control of ram speed and ram position. In modern installations this feature is very significant because the press is usually integrated with a manipulator. The stroke position of the press and the motions of the manipulator are computer controlled. As a result, the entire open-die forging operation can be programmed for given initial and final stock shape and workpiece material.

Dies

Most open-die forgings are produced in a pair of flat dies--one attached to the hammer or to the press ram and the other attached to the anvil. Swage dies (curved), V-dies, and V-die and flat-die combinations are also used (Fig. 16). Occasionally, a combination of a flat die and a swage die is used. Dies are attached to platens and rams or are held on the anvil manually with handles.

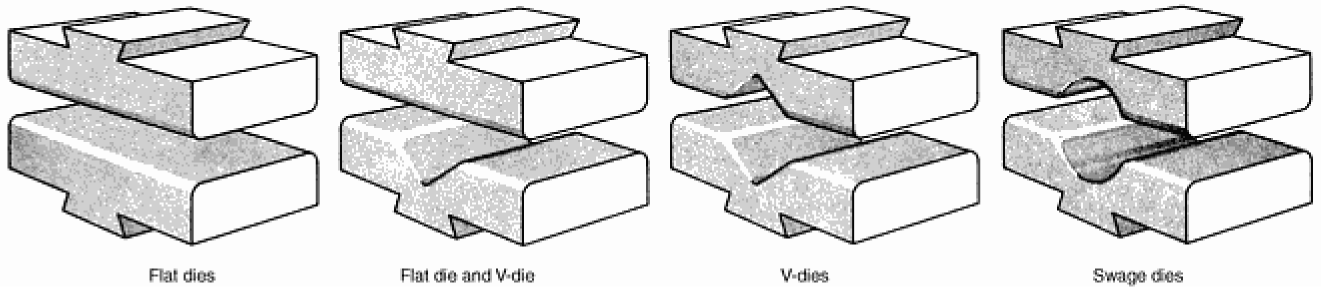


Fig. 16 Four types of die sets commonly used in open-die forging

Steels used for dies for open-die forging are often the same as those used for impression dies in closed-die forging--for example, 6G or 6F2 die-block steels (compositions of these steels can be found in Table 2). Alloy steels such as 4150 give satisfactory results for small dies. Some forgers prefer a higher carbon steel and use a 0.70% carbon, 4300 grade (such as 4370, although this is not a standard steel).

The hardness of dies for open-die forging is generally lower than the hardness of impression dies for closed-die forging. For 6G or 6F2, the usual hardness range is 302 to 331 HB. Dies made of 4150 or a similar alloy steel are usually heat treated to 277 to 321 HB.

Parallelism. If the faces of a set of dies mounted in a hammer or press are not parallel, the deviation creates a taper on the forgings that may be out of tolerance. Tolerances for parallelism vary to some extent with the size of the dies. Fairly large dies (dies 965 by 510 mm, or 38 by 20 in., for example) should be parallel within 1.6 mm ($\frac{1}{16}$ in.) front to back and side to side. For smaller dies, closer parallelism can be maintained.

Life of dies for open-die forging is longer than that of impression dies for closed-die forging. Because of the wide variety of forgings produced on the same open dies, life is usually expressed in production hours rather than in number of forgings. It is not unusual for dies to operate in a hammer for 600 h before they require redressing. Dies are usually designed to permit eight to ten redressings, which is equivalent to 4800 to 6000 h total life.

Auxiliary Tools

To assist in forging production, mandrels, saddle supports, sizing blocks (spacers), ring tools, bolsters, fullers, punches, drifts (expansion tools), and a wide variety of special tools (for producing special shapes) are used. Because most auxiliary tools are exposed to heat, they are usually made from the same steels as the dies.

Closed-Die Forging in Hammers and Presses

Closed-die forging, often referred to as impression-die forging, accounts for the bulk of commercial forging production. As the name implies, two or more dies containing impressions of the part shape are brought together causing the workpiece to plastically deform with the metal flow restricted by the die contours.

The forging stock, generally round or square bar, is cut to length to provide the volume of metal needed to fill the die cavity, in addition to an allowance for flash and sometimes for a projection for holding the forging. The flash allowance is, in effect, a relief valve for the extreme pressure produced in closed dies. Flash also acts as a brake to slow the outward flow of metal in order to permit complete filling of the desired configuration.

Most closed-die forging is performed at elevated temperatures and is known as hot forging. Both the forging stock and the die are preheated prior to forging. Various types of electric and fuel-fired furnaces are used for heating the forging stock, as well as resistance and induction heating. Die heating is discussed in the section "Die Heating."

Also in the closed-die category are cold forging and warm forging processes. Cold forging processes technically include such categories as coining, which is covered in the section "Coining." Cold forgings, produced at about room temperature are generally symmetrical and typically weigh less than 11 kg (25 lb). Because of their extreme dimensional precision and fine surface finish they often need little or no further machining. Production rates are very high with long die life.

In warm forging, technically and metallurgically similar to cold forging, the workpiece is heated to "a few" hundred degrees above room temperature, but well below hot-forging temperatures. Warm forging may be selected over cold forging for higher carbon grades of steel or to eliminate subsequent annealing.

Capabilities of the Process

Closed-die forging is used for both low-volume or high-volume production. In addition to producing final, or nearly final, metal shapes, closed-die forging controls grain-flow direction, often improving mechanical properties in the longitudinal direction of the workpiece.

Size of forgings produced in closed, impression dies can range from a few ounces to several tons. The maximum size that can be produced is limited only by the equipment that is available for handling and for forging. Steel forgings weighing as much as 25,400 kg (56,000 lb) have been closed-die forged. Typically, however, more than 70% of the closed-die forgings produced weigh 0.9 kg (2 lb) or less.

Shapes. Complex nonsymmetrical shapes that require a minimum number of operations for completion are suitable for closed-die forging. In addition, the process can be used in combination with other processes to produce parts having greater complexity or closer tolerances than are possible by forging alone. Cold coining and the assembly of two or more closed-die forgings by welding are examples of other processes that can extend the useful range of closed-die forging.

Forging Materials. Materials selected for closed-die forgings must satisfy two basic requirements. First, the material strength (or flow stress) must be low to hold die pressures to within the capabilities of practical die materials and constructions. Also, the forgeability of the material (its ability to deform without failure) must be equal to the amount of deformation required in the die. A comparison of the forgeability of various metals and alloys can be found in the article "Forging of Specific Metals and Alloys" later in this Section.

Classification of Closed-Die Forgings

Closed-die forgings are generally classified as blocker-type, conventional, and close-tolerance.

Blocker-type forgings are produced with generous allowance for finishing. These forgings are produced in relatively inexpensive dies, but their weight and dimensions are somewhat greater than those of counterpart conventional closed-die forgings. Often blocker-type forgings are specified when only a small number of forgings are required and the cost of machining parts to final shape is not excessive.

Blocker-type forgings can be produced in metal die blocks containing cavities of simple shape, or with stops and gages that the forging producer has in stock. These are called "loose" tools because they are not attached to the ram or anvil but are held in position on a bottom flat die by a handle. Loose tooling can be used to produce a variety of simple shapes, on short notice, without the cost of dies.

Because they lack the detail and the dimensional accuracy of forgings completed in finisher dies by conventional closed-die forging methods, forgings produced in loose tooling usually require substantially more machining to provide a finished part. Figure 17 shows specific examples.

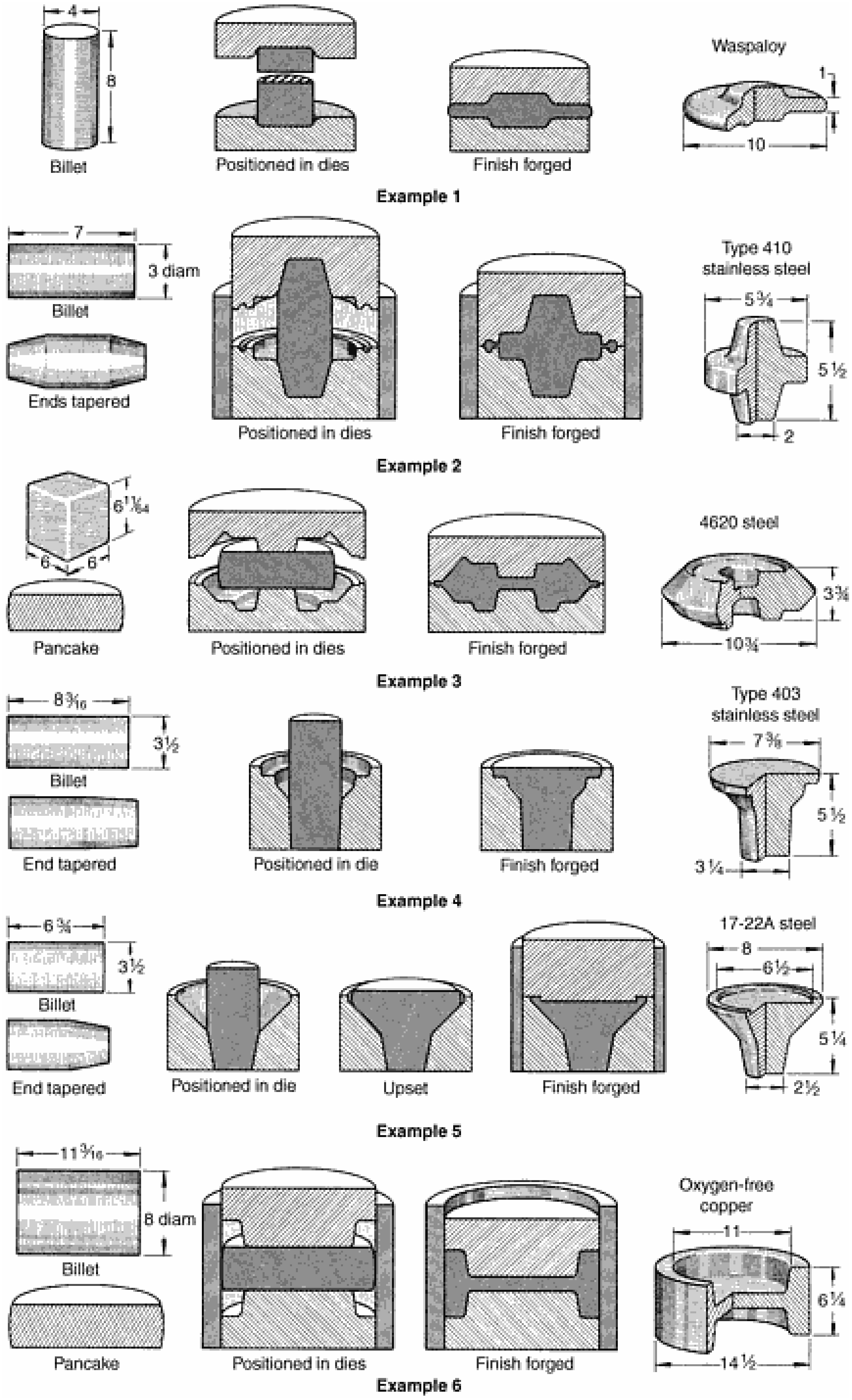

4
8
Billet
Positioned in dies
Finish forged
Waspaloy
1
10
Example 1
7
3 diam
Billet
Ends tapered
Positioned in dies
Finish forged
Type 410
stainless steel
5 3/4
5 1/2
2
Example 2
6 11/64
6
6
Pancake
Positioned in dies
Finish forged
4620 steel
3 3/4
10 3/4
Example 3
8 3/16
3 1/2
Billet
End tapered
Positioned in die
Finish forged
Type 403
stainless steel
7 3/8
5 1/2
3 1/4
Example 4
6 3/4
3 1/2
Billet
End tapered
Positioned in die
Upset
Finish forged
17-22A steel
8
6 1/2
5 1/4
2 1/2
Example 5
11 3/16
8 diam
Billet
Pancake
Positioned in dies
Finish forged
Oxygen-free
copper
11
6 1/4
14 1/2
Example 6

Fig. 17 Production of six blocker-type forgings with loose tooling in hammers. Dimensions are in inches.

Conventional closed-die forgings are the most common. They can be complex in shape with tolerances that fall within the broad range of general forging practice. Because they are made closer to the shape and dimensions of the final part than blocker-type forgings, they are lighter with more detail.

Close-tolerance forgings, obviously, are held to tighter dimensional tolerances than conventional forgings. Little or no machining is required after forging because close-tolerance forgings are made with less draft and with thinner walls, webs, and ribs. These forgings cost more and require higher forging pressures per unit of plan area than conventional forgings. However, the higher forging cost is sometimes justified by a reduction in machining cost. Additional information on close-tolerance forgings can be found in the subsection "Precision Forging."

Die Impressions. Several different types of can be used in a forging die, each type being designed to serve a specific function. In a forging sequence that incorporates several types of impressions, each impression should be considered for the specific function that it is to perform, both by itself and in relation to the preceding and succeeding impressions. In particular, the design of each impression should provide for location of the workpiece in the succeeding die impression.

Finishers. The finisher impression gives the final overall shape to the workpiece. In this impression excess metal is forced out into the flash. Despite its name, the finisher impression is not necessarily the last step in the production of a forging. Bending or hot coining sometimes follows to produce the final shape or dimensions to the forged part after it has passed through the finisher impression and the trimming die.

Preforming or Roughing. In any form of hammer forging, parts usually are preformed or roughed by one or a sequence of preliminary steps in impressions called fullers, edgers, rollers, flatteners, benders, splatters, and blockers (Fig. 18). Blockers are also used in press forging.

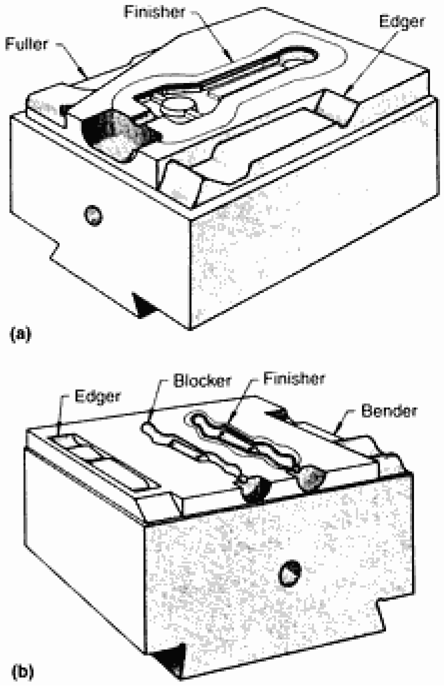


Fig. 18 Typical multiple-impression hammer dies for closed-die forging

Fullers. This die impression is used to reduce the cross section and to lengthen a portion of the forging stock. In longitudinal cross section, the fuller is usually elliptical or oval, to obtain optimum metal flow without producing laps, folds, or cold shuts. (Reducing and lengthening forging stock between flat portions of die surfaces is called drawing, rather than fullering.) Fullers are used in combination with edgers or rollers, or as the only impression prior to the blocker or finisher.

Because fullering usually is the first step in the forging sequence and generally uses the least amount of forging load, the fuller is almost always placed on the extreme edge of the die (Fig. 18a).

Edgers. Used to redistribute and proportion stock for heavy sections to be further shaped in blocker or finisher impressions, the action of the edger is opposite to that of the fuller. A forged connecting rod, for example, is first reduced in a fuller to prepare the slender central part of the rod and then worked in an edger to proportion the ends for the boss and crank shapes.

The edger impression can be open at the side of the die block, Fig. 18(a), or confined, (Fig. 18b). An edger is sometimes used in combination with a bender in a single die impression to reduce the number of forging blows necessary to produce a forging.

Rollers round the stock (for example, from a square billet to a round bar) or redistribute the mass prior to the next impression. The stock usually is rotated, and two or more blows are needed to roller the stock.

The operation of a roller impression is similar to that of an edger, but the metal is partially confined on all sides, with shapes in the top and bottom dies resembling a pair of shallow bowls. Because of the cost of sinking the die impressions, rollering is more expensive than edging when both operations require the same number of blows.

Flatteners widen the work metal so it more nearly covers the next impression or, with a 90° rotation, to reduce the width to within the dimensions of the next impression. The flattener station can be either a flat area on the face of the die or an impression in the die to give the exact size required.

Benders. A portion of the die can be used to bend the stock, generally along its longitudinal axis, in two or more planes. There are two basic designs of bender impressions: free flow and trapped stock.

In bending with a free-flow bender, Fig. 18(b), one end or both ends of the forging are free to move into the bender. A single bend is usually made. This type of bending can cause folds or small wrinkles on the inside of the bend.

The trapped-stock bender usually creates multiple bends. In trapped-stock bending, the stock is gripped at both ends as the blow is struck and the stock in between is bent. Because the metal is held at both ends, it usually is stretched during bending. There is a slight reduction in cross-sectional area in the bend, and the work metal is less likely to wrinkle or fold than in a free-flow bender.

Stock that is to be bent may require preforming by fullering, edging, or rollering. Bulges of extra material can be provided at the bends to prevent formation of kinks or folds in free-flow bending. This is particularly necessary for sharp bends. The bent preform usually is rotated 90° as it is placed in the next impression.

Splitters. In making "forked" forgings, part of the work metal is split to conform more closely to the subsequent blocker impression. In splitting, the stock is forced outward from its longitudinal axis by the action of the splitter. Generous radii should be used to prevent formation of cold shuts, laps, and folds.

Blockers. The blocker impression is used in both hammer and press forging. The blocker immediately precedes the finisher impression to refine the shape of the metal. Usually, the blocker omits those details that restrict metal flow in finishing. A blocker may be a streamlined model of the finisher. Streamlining helps the metal to flow around radii, reducing the possibility of cold shuts or other defects.

Sometimes, the blocker impression is made by duplicating the finisher impression in the die block and then rounding it off as required for smooth flow of metal. Preferred, however, is to make the blocker impression slightly narrower and deeper than the finisher impression with a volume that is equal to, or only slightly greater than, that of the finisher. This minimizes die wear at the parting line in the finisher impression.

For parts that include deep holes or bosses, the blocker can be a gathering operation. It can sink a volume of metal to one side of the forging, which then can be forced through to the other side in the finisher impression to fill a high boss.

Blocker impressions are also used to reduce wear on the finisher cavity. Therefore, a blocker is often included in the series of dies for long forging runs, or in production of close-tolerance forgings, to prolong the life of the finisher impression.

Process Variables

Flashing design, die preheating, and trimming are several characteristics of closed-die forging that must be considered.

Flash. Forging pressures are determined in part by flash thickness and flash-land width (Fig. 19). Essentially, forging pressure increases with decreasing flash thickness and increasing flash-land width. These variables control restriction, frictional forces, and metal temperatures at the flash gap.

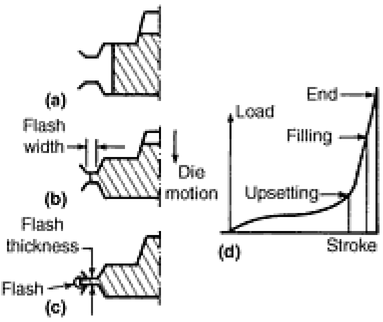


Fig. 19 Metal flow and load-stroke curve in closed-die forging. (a) Upsetting. (b) Filling. (c) End. (d) Load-stroke curve

During a typical forging press stroke, loads are relatively low until the more difficult details in the die are partly filled and the metal reaches the flash opening. At this point, two conditions must be fulfilled: a sufficient volume of metal must be trapped within the confines of the die to fill the remaining cavities and extrusion of metal through the narrowing gap of the flash opening must be more difficult than filling of the more intricate detail in the die.

As the dies continue to close, the load increases sharply until the die cavity is filled completely. Ideally, at this point, the cavity pressure provided by the flash geometry should be just sufficient to fill the entire cavity, and the forging should be completed. A cavity can be filled with various flash geometries provided that there is always a sufficient supply of material in the die. In general, the flash thickness should increase with increasing forging weight, while the ratio of flash width to flash thickness (*w*/*t*) decreases to a limiting value.

Die Heating. Dies should be heated to at least 120 °C (250 °F), and preferably to 205 to 315 °C (400 to 600 °F), before forging begins. "Warmers" (pieces of hot metal) placed between the die faces, or torches, are used. Dies can be heated in ovens before set up in the hammer or press. Temperature-indicating crayons can be used to measure surface temperature. Cold dies can break when a hot billet is placed on them.

Trimming. Several processes are used to trim flash after forging. The method used will depend on the production quantity and size of the parts. Trimming can sometimes eliminate a machining operation.

For small quantities or for large forgings, hand grinding, sawing, or machining can be used to remove the flash. In large quantities, most forgings are die trimmed.

Cold trimming usually refers to die trimming below 150 °C (300 °F). This method, often used, especially for small forgings, can be done at any time; it need not be a part of the forging sequence. No reheating of the forgings is needed. Another advantage is that the trimming blades can be adjusted to shear the flash to a smooth surface that does not require machining.

Almost all of the common forging alloys can be cold trimmed. Some may require annealing or other heat treatment after forging before they can be cold trimmed. As a rule of thumb, a forging can be cold trimmed if, after forging, its tensile strength does not exceed 690 MPa (100 ksi) or hardness not over 207 HB.

Cold trimming may require great press capacity, however. Thus, hot trimming may be selected. Hot trimming is done as low as 150 °C, or 300 °F (for nonferrous alloys), and as high as 980 °C (1800 °F) or above for steels and other ferrous alloys.

Friction and Lubrication in Forging

In forging, friction greatly influences metal flow, pressure distribution, and load and energy requirements. In addition to lubrication effects, the effects of die chilling or heat transfer from the hot material to colder dies must be considered. For example, for a given lubricant, friction data obtained from hydraulic press forging cannot be used for mechanical press or hammer forging even if die and billet temperatures are comparable.

In forging, the ideal lubricant is expected to:

- Reduce sliding friction between the dies and the forging in order to reduce pressure requirements, to fill the die cavity, and to control metal flow
- Act as a parting agent and prevent local welding and subsequent damage to the die and workpiece surfaces
- Possess insulating properties so as to reduce heat losses from the workpiece and to minimize temperature fluctuations on the die surface
- Cover the die surface uniformly so that local lubricant breakdown and uneven metal flow are prevented
- Be nonabrasive and noncorrosive so as to prevent erosion of the die surface
- Be free of residues that would accumulate in deep impressions
- Develop a balanced gas pressure to assist quick release of the forging from the die cavity; this characteristic is particularly important in hammer forging, in which ejectors are not used
- Be free of polluting or poisonous components and not produce smoke upon application to the dies

No single lubricant can fulfill all of the requirements listed above; therefore, a compromise must be made for each specific application.

Various types of lubricants are used, and they can be applied by swabbing or spraying. The simplest is a high flash point oil swabbed onto the dies. Colloidal graphite suspensions in either oil or water are frequently used. Synthetic lubricants can be employed for light forging operations. The water-base and synthetic lubricants are extensively used primarily because of cleanliness.

Hot Upset Forging

Hot upset forging (also called hot heading, hot upsetting, or machine forging) is essentially a process for enlarging and reshaping some of the cross-sectional area of a bar, tube, or other uniform, usually round, section. Basically, the heated forging stock is held between grooved dies while pressure is applied to the end of the stock in the direction of its axis by a heading tool. The tool spreads (upsets) the end by metal displacement (Fig. 20).

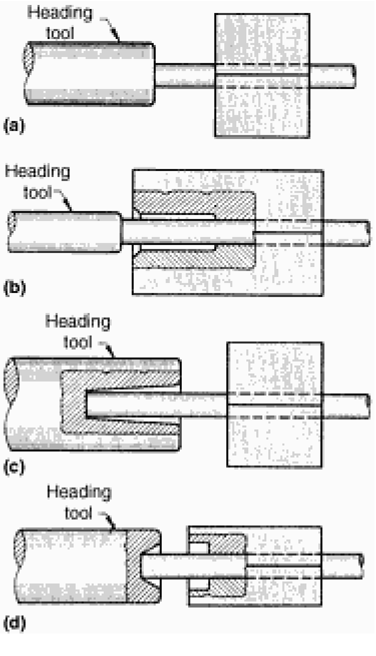


Fig. 20 Basic types of upsetter heading tools and dies, showing the extent to which stock is supported. (a) Unsupported working stock. (b) Stock supported in die impression. (c) Stock supported in heading tool recess. (d) Stock supported in heading tool recess and die impression

Applicability

Although hot upsetting originally was restricted to single-blow heading of parts such as bolts, present-day machines and tooling permit the use of multiple-pass dies that can produce complex shapes accurately and economically. The process now is widely used for producing finished forgings ranging in complexity from simple headed bolts or flanged shafts to wrench sockets that require simultaneous upsetting and piercing. Parts requiring center (not at bar end) or offset shaping also can be upset.

In many instances, hot upsetting is used to prepare stock for subsequent hammer or press forging. Occasionally, hot upsetting is also used as a finishing operation following hammer or press forging, such as in making crankshafts.

Because the transverse action of the moving die and longitudinal action of the heading tool can forge in both directions, either separately or simultaneously, hot upset forging is not limited to simple gripping and heading operations. The die motion can be used for swaging, bending, shearing, slitting, and trimming. In addition to upsetting, heading tools are used for punching, internal displacement, extrusion, trimming, and bending.

In upset forging, the working stock usually is confined in the die cavities during forging. The upsetting action creates pressure, similar to hydrostatic pressure, which causes the stock to fill the die impressions completely. Thus, a wide variety of shapes can be forged and removed from the dies by this process.

Work Material and Size. Although most forgings produced by hot upsetting are of carbon or alloy steel, the process can be used for shaping any forgeable metal. The size or weight of workpiece that can be hot upset is limited only by the capabilities of available equipment; forgings ranging in weight from less than an ounce to several hundred pounds can be produced by this method.

Upset Forging Equipment

A typical machine for hot upset forging is mechanically operated from a main shaft with an eccentric drive that operates a main slide, or header slide, horizontally. The action of the header slide is similar to that of the ram in a mechanical press. Power is supplied to a machine flywheel by an electric motor. A flywheel clutch provides for "stop motion" operation, placing movement of the slides under operator control.

Forging takes place in three die elements: two gripper dies (one stationary and one moved by the die slide), which have matching faces with horizontal grooves to grip the forging stock and hold it by friction, and a heading tool, or "header," which is carried by the header slide in the plane of the work faces of the gripper dies and aligns with the grooves in these dies (Fig. 21). The travel of the moving die is designated as the "die opening," and its timed relation to the movement of the header slide is such that the dies close during the early part of the header-slide stroke. The part of the forward header-slide stroke that takes place after the dies are closed is known as the "stock gather," and the amount that the returning header slide travels before the moving die starts to open is called the "hold on," or the "hold."

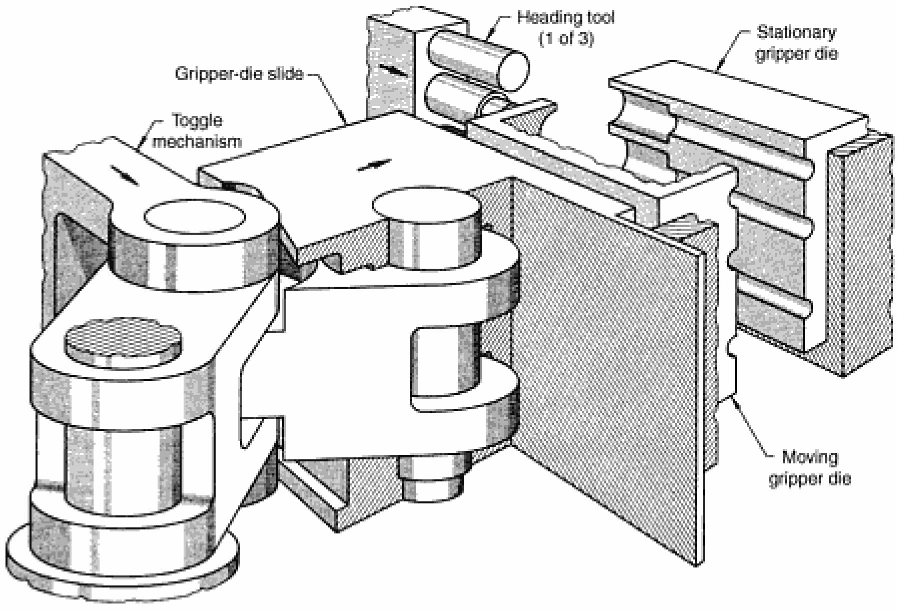


Fig. 21 **Basic actions of the gripper dies and heading tools of an upsetter**

The die opening determines the maximum diameter of upset that can be formed on a given machine, transferred between the dies and withdrawn through the throat, without pushing the workpiece forward and lifting it out over the top. The diameter of the stock, rather than the stock gather, determines the amount of stock that can be upset; the stock gather, however, has an important bearing on the depth to which internal displacement can be carried. The height of the die determines the number of progressive operations that can be accommodated in one set of dies.

Although some forgings are produced by a single stroke of the ram, most shapes require more than one pass to complete. The upsetter dies may incorporate several different impressions or "stations." The stock is moved from one impression (or station) to the next in sequence, to give the forging a final shape. Each move constitutes a "pass." Three or more passes are commonly used to complete the upset, and if flash removal (trimming) is a part of the forging operation, another pass is added.

Piercing and shearing passes can also be incorporated in the dies. In single-blow, solid-die machines, the gripper dies are replaced by a shear arm and shear blade. A long heated bar of forging stock is placed in a slot and pushed against a stop. As the machine is actuated, either automatically or by means of a foot pedal, a motion similar to that of a conventional upsetter occurs, except that, instead of the dies closing, a section of the bar is sheared off. While the shear slide is moving, a cam actuates a transfer arm, which moves until it contacts the stock. The stock, now positioned between the shear blade and the transfer arm, is moved into proper position between the punch and the die. As the punch advances and contacts the stock, the shear blade and the transfer arm move apart. The punch continues its advance, and the forging is produced in a single blow. Ejector pins push the forging from the die, and it drops onto an underground conveyor. Another heated bar of forging stock is pushed against the stop, and the cycle is repeated.

Tool Materials

For short runs, solid dies are made of lower-alloy steels such as 4340, 6G, or 6F3. For runs of approximately 1000 pieces, higher-alloy hot work steels are commonly used for small dies or inserts in large dies. Two important advantages in the use of punch and die inserts are that they can be replaced when worn out and that, in many applications, two or more different parts can be forged with a master block by changing inserts.

Die Cooling and Lubrication

Normal practice is to keep dies below 205 °C (400 °F) during forging. In some low-production operations, no coolant is required to keep dies below this temperature. In most applications, however, a water spray (sometimes containing a small amount of salt or graphite) is used as a coolant.

Die lubrication slows production and is not widely used in upsetting of steel. Because of the die action in upsetting, parts are less likely to stick than in hammer or press forging. In deep punching and piercing, however, sticking may be encountered, thus requiring a lubricant. An oil-graphite spray is effective and can simultaneously provide adequate cooling. A recirculated suspension of alumina in water is used in some high-production operations.

Roll Forging

Roll forging (also known as hot forge rolling) is a process for reducing the cross-sectional area of heated bars or billets by passing them between two driven rolls that rotate in opposite directions and have one or more matching grooves in each roll. The principle involved in reducing the cross-sectional area of the work metal in roll forging is essentially the same as that employed in rolling mills to reduce billets to bars.

Applications

Any metal that can be forged by other methods can be roll forged. Heating times and temperatures are the same as those used in the forging of metals in open or closed dies.

Roll forging can be used either as the sole or main operation in producing a shape. Generally this involves the shaping of long, thin, usually tapered parts. Typical examples are airplane propeller-blade half sections, tapered axle shafts, tapered leaf springs, table-knife blades, hand shovels and spades, various agricultural tools (such as pitchforks), and tradesman's tools (such as chisels and trowels). Roll forging is sometimes followed by the upsetting of one end of the workpiece to form a flange, as in the forging of axle shafts.

Roll forging also is used as a preliminary operation to save material and number of hits in subsequent forging in closed dies. Applications in this case include preliminary shaping of stock prior to forging in impression dies in either a press or hammer, thus eliminating a fullering or blocking operation. Crankshafts, connecting rods, and other automotive parts are typical products that are first roll forged from billets to preform stock and then finish forged in a press.

Equipment for Roll Forging

In machines for roll forging (often called forge rolls, reducer rolls, back rolls, or gap rolls), the driving motor is mounted at the top of the main housing (Fig. 22). The motor drives a large flywheel by means of V-belts. In turn, the flywheel drives the roll shafts, to which the roll dies are attached, through a system of gears. Forging rolls are available in numerous sizes and have the capacity to roll blanks up to 127 mm (5 in.) thick and 1020 mm (40 in.) long.

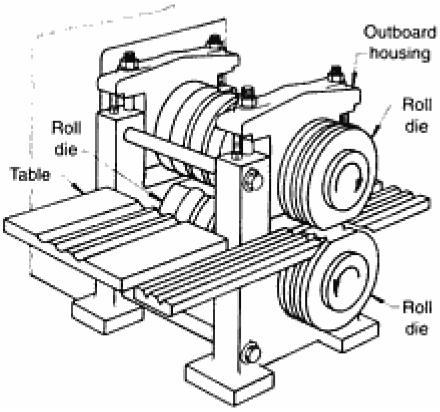


Fig. 22 **Roll-forging machine with outboard housing**

Roll dies are bolted to the roll shafts, which rotate in opposite directions during operation. Roll dies (or their effective forging portion) usually occupy about one-half the total circumference; therefore, at least some forging action takes place during half of the revolution. Machines can be operated continuously or stopped between passes, as required. In the roll forging of long tapered workpieces, the more common practice is to operate the machine intermittently.

Roll Dies

Roll dies are of three types: flat back, semicylindrical, and fully cylindrical. Each type is shown in Fig. 23(a).

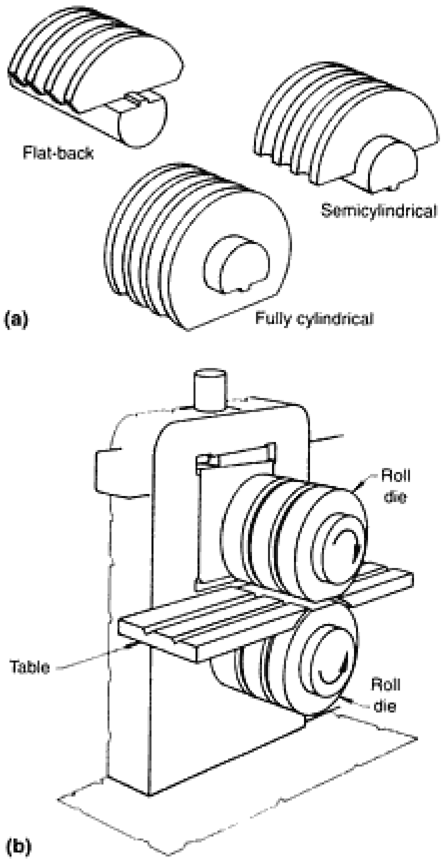


Fig. 23 (a) Dies used in roll forging. (b) Overhang-type roll forger that utilizes fully cylindrical dies

Flat-back dies are primarily used for short-length reductions. They are bolted to the roll shafts and can be easily changed.

Semicylindrical dies are well suited to the forging of medium-length workpieces. Most are true half cylinders (180°), although some (particularly in large sizes) may encompass up to 220° of a circle to provide sufficient periphery for the specific application. When each die section is no more than 180°, the dies can be made by first machining the flat surfaces of the half rounds for assembly, clamping the half rounds together, and then boring and finishing.

Fully cylindrical dies are used to forge long members, sometimes in an overhang-type machine (Fig. 23b). They are built up with rings, with a cutaway portion just large enough to feed in the forging stock. Fully cylindrical dies are sometimes more efficient than semicylindrical or flat-back dies because of the larger periphery available for the forging action. However, one disadvantage of fully cylindrical dies is that the small opening prevents continuous operation; consequently, motion must be controlled by a clutch and a brake.

Steels for roll dies do not differ greatly from those used for dies in hammer, press, and upset forging. However, because roll dies are subjected to less impact than dies in other types of forging, they can be made of die steels that are somewhat higher in carbon content, which is helpful in prolonging die life.

High-Energy-Rate Forging

High-energy-rate forging (HERF), sometimes called high-velocity forging, is a closed-die, hot- or cold-forging process in which the stored energy of high-pressure gas is used to accelerate a ram to unusually high velocities to deform the workpiece. Ideally, the final configuration of the forging is developed in one blow or, at most, a few blows. In HERF, the velocity of the ram, rather than its mass, generates the major forging force. The maximum impact velocity of HERF machines is approximately three to four times that of conventional drop hammers. Typically, the ram velocity at impact in the HERF machine is in the range of 5 to 22 m/s (16 to 72 ft/s); ram velocities range from 4.5 to 9.1 m/s (15 to 30 ft/s) for a power-drop hammer and from 3.6 to 5.5 m/s (12 to 18 ft/s) for a gravity-drop hammer.

High-energy-rate machines can be used to hot forge parts of the same general shapes as those produced with conventional hammers and presses. However, the work metal must be capable of undergoing extremely rapid deformation rates as it fills the die cavity without rupturing it. In HERF, the high ram velocities forge parts with thin webs, high-rib, height-to-width ratios, and small draft angles to profiles sufficiently accurate that machining allowance can sometimes be as little as 0.500 mm (0.0197 in.). Even parts made of difficult-to-forge metals can be formed close to finished dimensions in a few blows and often without reheating.

Process Advantages and Limitations

Advantages. When evaluating high-energy-rate forging in relation to conventional forging, both the machine advantages and process advantages, as a result of the high velocities, must be considered. The machine advantages are beyond dispute. For a given forming capacity, high-speed machines are much smaller than conventional forging machines, and they require much less installation/foundation and therefore a lower capital investment. These advantages arise because the principle used in these machines involves the conversion of the kinetic energy of a ram/platen into forming work. Kinetic energy is proportional to the square of the impact velocity; therefore, a threefold increase in impact speed produces a nine-fold increase in forming energy. High-energy-rate forging machines are typically one-ninth the bulk and weight of equivalent slow-speed machines. Although the finished forging is generally made in one high-speed blow, some machines can be fired two or three times before the work metal has cooled below the forging temperature.

The process advantages are not as obvious as the machine advantages and depend on the particular application under consideration. In general, with HERF, complex parts can be forged in one blow from a billet or a preform. Many metals that are difficult to forge by other methods can be successfully forged by HERF.

Dimensional accuracy, surface detail, and, often, surface finish are better with HERF than other techniques. Draft allowances, both internal and external, can be reduced or, in some applications, eliminated. Forgings are made to size or with a minimum of machining allowance. Reduced machining lowers the induced mechanical stress and minimizes the cutting of end grain, which improves the stress-corrosion resistance of some metals, notably aluminum.

Deep, thin sections can be HERFed because the rapidity of the blow provides little time for heat transfer to the die walls. Severe deformation possible with HERF provides a high degree of grain refinement in some metals.

Limitations. The process, however, does have several limitations. Sharp corners and small radii cannot be forged without causing undue wear. The process is generally limited to symmetrical parts, although some asymmetrical parts can be forged from preformed billets. High-energy-rate forging part size is limited to approximately 11 to 12 kg (24 to 26 lb) for carbon steel forgings and to lesser weights for forgings made of stainless steel or heat-resistant alloys.

The production rate is about the same as in hammer or hydraulic press forging but is slower than in mechanical press forging. However, dies must be carefully designed and fabricated in order to withstand the high impact; compressive prestressing of the die inserts by a shrink ring is a common practice.

High-Energy-Rate Forging Equipment and Production Rates

As described earlier, the three basic types of HERF machines are ram-and-inner-frame, two-ram, and controlled-energy-flow (counterblow) (refer to Fig. 4 and related text). The cycle time for a HERF machine is 12 to 20 s per piece, or a production rate of 180 to 300 parts per hour. Therefore, HERF machines can make parts to close profiles at production rates often comparable to those of drop-hammer and hydraulic presses. Adaptation of automatic transfer equipment to high-energy-rate forging further increases the production rates to levels competitive with manually operated mechanical presses. The machines are readily adaptable to automatic loading and unloading equipment. However, high-production runs or multiple runs of similar parts are needed to justify the cost of automatic handling equipment.

Dies

Closed dies and flash-and-gutter impression dies are used in HERF. The closed dies restrict the flow of metal and force it to fill the cavity completely; they are recommended because they require less material in the billet and permit closer dimensional control of the forging. Flash-and-gutter impression dies are generally used for thicker parts with more liberal dimensional tolerances.

As in conventional hammer forging, the force of the ram should be completely expended in deforming the workpiece. Impact between the upper and lower tools is potentially destructive. It can be avoided by control of processing conditions that significantly influence metal plasticity (such as temperature, volume, and die temperature and lubrication) and in some cases by selective placement of a protective ring around the upper die.

HERF Processing

Like conventional forging, HERF is performed over a broad range of temperatures, depending on the specific part, the material, and the design requirements. Three categories of HERF are hot forging, cold forging, and warm forging.

Hot Forging. Under the most favorable conditions, hot HERF is used to forge parts that cannot be forged with conventional machines. Complex parts and components with thin sections have been produced; webs and ribs 3.18 mm (0.125 in.) thick and central ribs 4.76 mm (0.1875 in.) thick are technically feasible. However with pneumatic-hydraulic HERF machines, such results can often be obtained only at the expense of die life in view of their long dwell times.

Cold HERF at high speeds improves die lubrication, which lowers the fictional forces, which in turn improves metal flow and surface finish of the components. The process is practically adiabatic; therefore, with soft materials, such as aluminum and copper, some softening occurs. Forging forces and pressures are generally higher than those obtained at conventional speeds, although energy requirements may well be lower.

Warm HERF, in comparison to hot HERF, is free of scale and therefore produces better surface quality, high precision, and improved tool life. In relation to cold HERF, the process significantly lowers tool loads, permitting a wider range of both component sizes and available materials to be forged without appreciable deterioration in component material properties.

Metals HERFed

Metals best suited to HERF are those that withstand very high deformation rates without rupturing. High-energy-rate forging is particularly suited to alloys that require high forging temperatures and pressures, especially when thin webs or unusual design features are required. Low-carbon steels, refractory metals, and nickel alloys that have broad forging temperature ranges can be forged. Metals with low ductility under rapid deformation rates, such as magnesium and beryllium alloys, cannot be forged by high-velocity methods.

Heating that is caused by rapid deformation, if excessive, may cause incipient melting and serious rupturing when forging to large reductions. The metals affected in this manner include high-carbon steels, high-strength aluminum alloys, and nickel-base, heat-resistant alloys. Increased temperatures during forging can cause β-embrittlement in some titanium alloys.

Ring Rolling

Ring rolling is used to manufacture seamless annular forgings that are accurately dimensioned and have circumferential grain flow. Ring rolling usually requires less input material than alternative forging methods, and it is applicable to production in any quantity.

Operating Principles. In ring rolling (Fig. 24), a heated doughnut-shaped blank, preformed on a press or forging hammer, is placed over a mandrel of slightly smaller diameter than the hole in the blank. The roll gap between the mandrel (undriven) and a larger diameter driven main roll is progressively reduced. Friction between the main roll and the ring causes the ring to rotate, and the ring in turn rotates the bearing-mounted mandrel. As the radial cross section of the ring decreases, circumferential extrusion occurs in the direction of ring rotation, and the ring diameter grows. The work rolls can be plain, producing uniformly rectangular ring cross sections or may have grooves or flanges to produce contoured ring cross sections. Ring height is controlled either by main roll shape or by the use of axial rolls set diametrically across the ring from the mandrel and main roll pass.

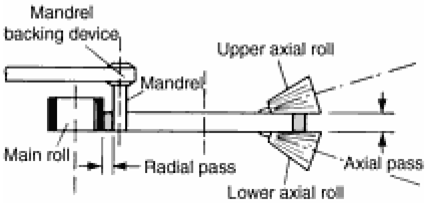


Fig. 24 Operational principles of a horizontal ringrolling mill

Products and Applications. Annular components can be ring rolled from any forgeable material. The configuration can range from very flat washer-shaped rings to long sleeve-type rings. Typical materials include carbon and low-alloy steels, copper, brass, aluminum and titanium alloys, and high-strength nickel and cobalt-base alloys, which are very difficult to form. Applications for seamless rolled rings include antifriction bearing races, gear rims, slewing rings, railroad wheel bearings, commutator rings, rotating and nonrotating rings for jet engines and other aerospace applications, nuclear reactor components, bevel ring gears, flanges of all kinds (including weld-neck flanges), sheaves, wheels, valve bodies, food-processing dies, and chain master links.

Sizes. About 90% of all rolled rings have outside diameters in the range from 240 to 980 mm (9.5 to 38.6 in.), heights (lengths) ranging from 70 to 210 mm (2.75 to 8.25 in.), and wall thicknesses between 16 and 48 mm (0.63 and 1.9 in.). A significant number of rings, however, are rolled outside the previously mentioned parameters, and it is not unusual to find outside diameters ranging from 75 mm to 8 m (3 in. to 26.25 ft), heights from 15 mm to 2 m (0.6 in. to 6.5 ft), and weights from 0.4 to 82,000 kg (0.9 to 181,000 lb).

Rotary Swaging of Bars and Tubes

Rotary swaging is used to reduce the cross-sectional area or otherwise change the shape of bars, tubes, or wires by repeated radial blows with two or more dies. The work is elongated as the cross-sectional area is reduced. The workpiece (starting blank) is usually round, square, or otherwise symmetrical in cross section, although other forms, such as rectangles, can be swaged.

Most swaged parts are round, the simplest being formed by reduction in diameter. However, swaging can also produce straight and compound tapers, contours on the inside diameter of tubing, and can change round to square or other shapes.

Applicability. Swaging can reduce tubes up to 355 mm (14 in.) in initial diameter and bars up to 100 mm (4 in.) in initial diameter. Hardness, tensile strength, and reduction in area of the work metal have the most significant effect on swageability. Type and homogeneity of microstructure also influence the ease of swaging and the degree to which a metal can be swaged.

Work Metals. Of the plain carbon steels, those with a carbon content of 0.20% or less are the most swageable. These grades can be reduced up to 70% in a cross-sectional area by swaging. As carbon content or alloy content is increased, swageability is decreased. Alloying elements such as manganese, nickel, chromium, and tungsten increase work metal strength and therefore decrease the ability of the metal to flow. Free-machining additives such as sulfur, lead, and phosphorus cause discontinuities in structure that result in splitting or crumbling of the work metal during swaging.

Metal flow during rotary swaging is not confined to one direction. Metal also moves opposite to the direction feed. The action of the metal moving against the direction of feed is termed "feedback." It results from slippage of the workpiece in the die taper when it is too steep.

Unless resisted, the workpiece rotates as the dies close. The speed of rotation is that of the roller cage. If rotation is permitted, swaging occurs in only one position on the workpiece, causing ovaling, flash, and sticking of the workpiece in the die. Resistance to rotation is manual when the swager is hand fed; mechanical means are used with automatic feeds.

Swaging Equipment. Rotary swaging machines are classified as standard rotary, stationary-spindle, creeping-spindle, alternate-blow, and die-closing (Fig. 25). All these machines are equipped with dies that open and close rapidly to provide the impact action that shapes the workpiece. Swagers allow the work to be fed into the taper entrance of the swaging dies.

The amount of diameter reduction per pass is limited by the design of the entrance taper of the dies or the area reduction capability of the machine. The results are expressed in terms of diameter reduction or area reduction.

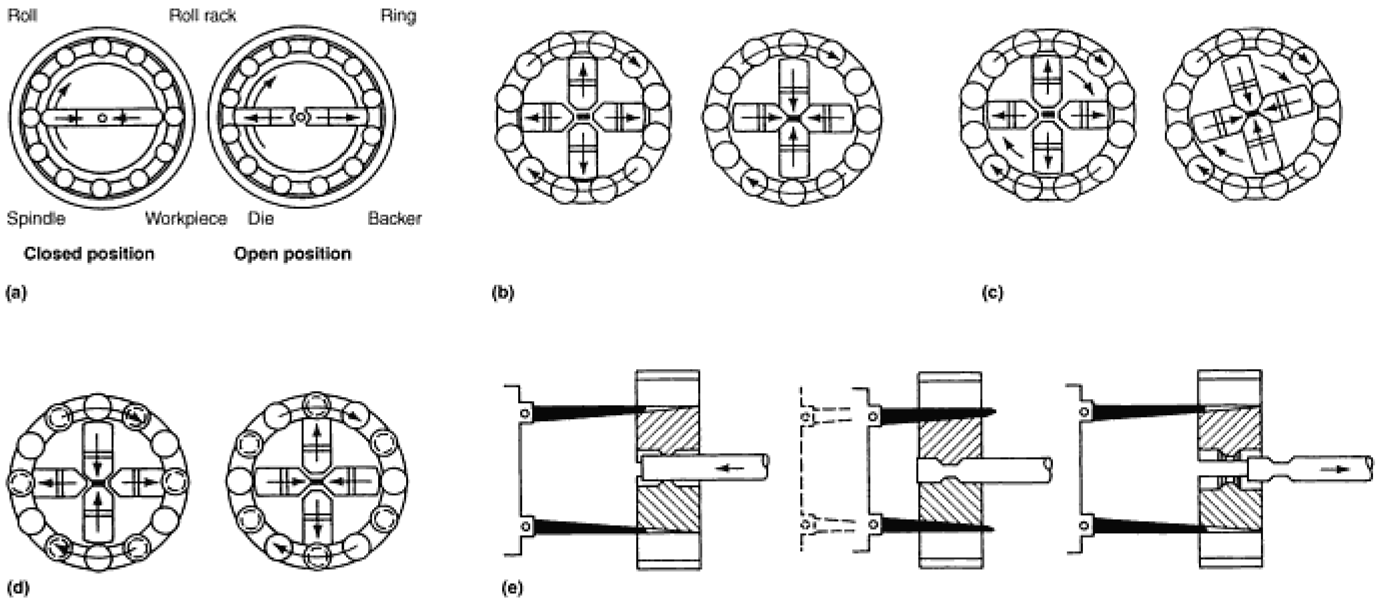


Fig. 25 Principle machine concepts for rotary swaging. (a) The standard rotary swager is a mechanical hammer that delivers blows (impact swaging) at high frequency, thus changing the shape of a workpiece by metal flow. This machine is used for straight reducing of stock diameter or for tapering round workpieces. (b) With stationary-spindle swagers, the spindle, dies, and work remain stationary while the head and roll rack rotate. These machines are used for swaging shapes other than round. (c) Creeping-spindle swaging employs the principles of both standard and stationary-spindle swaging. The spindle and dies are mounted on a shaft that rotates slowly inside the rapidly rotating roller cage, thus permitting more accurately controlled reciprocation of the dies. (d) Alternate-blow swaging is accomplished by recessing alternate rolls; when two opposing rollers hammer the dies, the rolls 90° away do not. (e) Die-closing swagers are essentially the same as standard rotary swagers. However, die-closing swagers feature a reciprocating wedge mechanism that forces closure of the taper back dies.

Radial Forging

Radial forging is performed with four-hammer machines (Fig. 26). The technology of the four-hammer forging machine differs from that of all other hot-forming methods. Conventional presses and hammers, or even rolling mills, use only two tools per forming operation. In the radial forging machine, however, a workpiece is formed at the same time by four hammers arranged in one plane, with maximum forging forces per die of up to 30 MN (3400 tonf). The free spreading that occurs between the two contacting tools in all conventional forging methods is eliminated. A radial press contacts the circumference of the workpiece equally and puts the entire surface of the workpiece under compressive stresses. These compressive stresses prevent the formation of surface cracks during the forging process and improve existing defects.

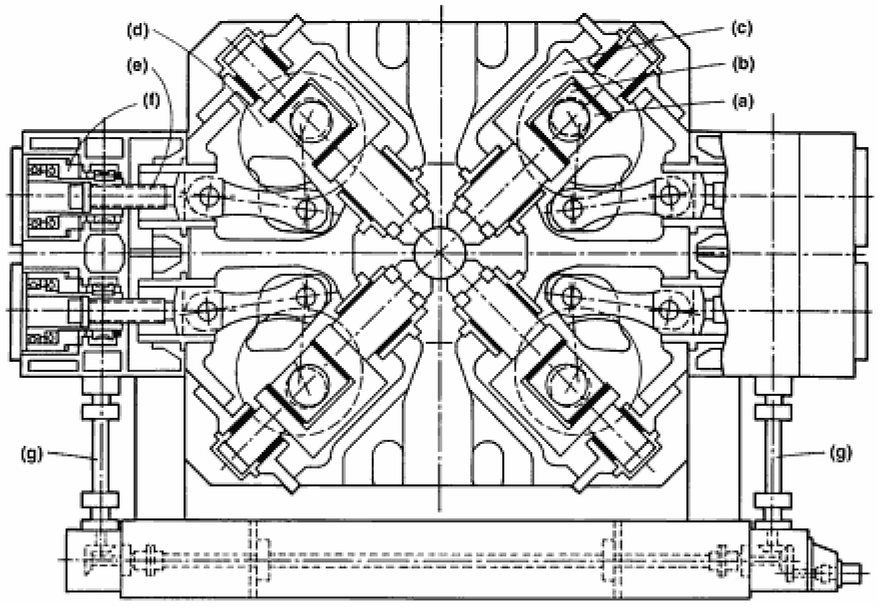


Fig. 26 Cross section of four-hammer radial forging machine with mechanical drive. (a) Eccentric shaft. (b) Sliding block. (c) Connecting rod. (d) Adjustment housing. (e) Adjusting screw. (f) Hydraulic overload protection. (g) Hammer adjustment drive shafts

Radial forging is sometimes confused in the literature with rotary (orbital) forging. In the rotary forging process described in "Rotary Forging," the axis of the upper die is tilted at a slight angle with respect to the axis of the lower die, and one or both dies rotate.

Current applications include bars with round, square, or rectangular cross section starting from ingots or blooms; stepped solid shafts and axles for locomotives, railroad cars, and trucks; stepped hollow shafts for components in the automotive and aircraft industries; preforms for turbine shafts or for subsequent closed-die forging; thick-wall tubes forged over a water-cooled mandrel; necks and bottoms of steel bottles; and couplings and tool joints.

Process advantages include high production rates (approximately four times greater rates for low-alloy steel products than for hammer or press forging; high-alloy steel production is six times higher), low energy consumption, and close tolerances (machining allowances are approximately 33% of the usual allowances on conventional forged products).

Equipment and Process. The four-hammer radial forging machine is basically a short-stroke mechanical press. The stroke of the forging connecting rods is initiated through eccentric shafts. The eccentric shafts are supported in housings that allow adjustment of the stroke position of the four forging connecting rods. One or two electric motors drive the eccentric shafts through a drive gear, which simultaneously controls the synchronization of the four eccentric shafts. The forging connecting rods can be changed in their stroke position either in unison or in pairs so that round, square, or rectangular cross sections can be forged.

Depending on its application, the part-handling system of the machine can be equipped with either one or two workpiece manipulators, which differ widely from conventional forging manipulators. In contrast to press or hammer forging, the workpiece axis in radial forging is always maintained on the forging machine centerline, regardless of the diameter. The manipulator moves only in the longitudinal direction. For exact guidance, the chuck head slides on a machine bed. During the forging of round cross sections, the chuck head rotates the workpiece in cycle with the forging hammers; that is, the rotary movement stops while the hammers are in contact with the workpiece. The rotary movement of the chuck-head spindle is synchronized with the hammer blows, eliminating twisting of the workpiece. The indexing positions of the chuck-head spindle required for forging squares, rectangles, or hexagons can be set automatically. The entire forging process, including loading and unloading, can be performed automatically by computer numerical control (CNC).

In radial forging, temperature of the workpiece increases with the deformation rate and the forming resistance of the material. The higher the forming resistance, the higher the temperature increase at each pass. Therefore, the temperature loss of the workpiece (because of heat radiation) can be compensated for by preselecting the deformation rate, forming the workpiece in temperature ranges with the highest material ductility. In practical terms, this means that all forming can be done in one heat from the ingot to finished bar steel, regardless of the alloy. Chamber furnaces, pit furnaces, and hearth-type furnaces can therefore be replaced by continuously operating furnaces.

Equipment for mandrel forging is available in different designs for the hot and cold forging of tubular workpieces. Long tubes with cylindrical bores are forged over a short mandrel, while short tubes are forged over a long mandrel. During hot forging, the mandrel is water cooled while in contact with the workpiece. Tungsten carbide mandrels are often used in cold forging for improved mandrel life.

Rotary Forging

Rotary forging, or orbital forging, is a two-die forging process that deforms only a small portion of the workpiece at a time in a continuous manner. Unfortunately, the term rotary forging is sometimes used to describe the process that is more commonly referred to as radial forging, causing some confusion in terminology. Figure 27 illustrates the differences between the two processes. As described in the section "Radial Forging," radial forging is a hot- or cold-forming process that uses two or more radially moving anvils or dies to produce solid or tubular components with constant or varying cross sections along their lengths.

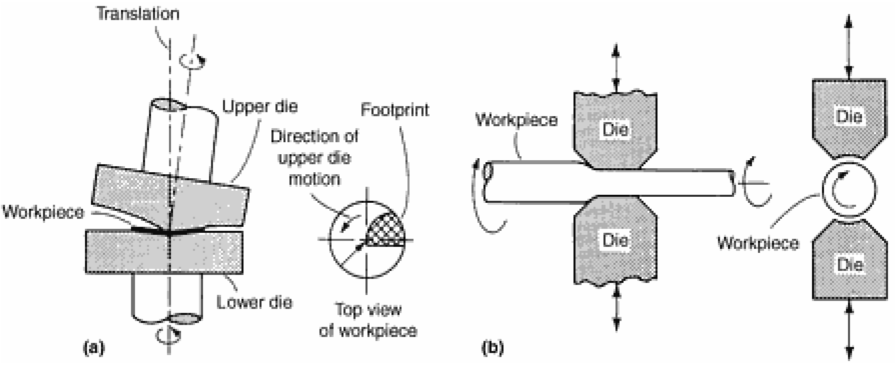


Fig. 27 Differences between rotary and radial forging. (a) In rotary forging, the upper die, tilted with respect to the lower die, rotates around the workpiece. The tilt angle and shape of the upper die result in only a small area of contact (footprint) between the workpiece and the upper die at any given time. Because the footprint is typically only about one-fifth the workpiece surface area, rotary forging requires considerably less force than conventional forging. (b) In radial forging, the workpiece is fed between the dies, which are given a rapid periodic motion as the workpiece rotates. In this manner, the forging force acts on only a small portion of the workpiece at any one time.

In rotary forging (Fig. 27a), the axis of the upper die is tilted at a slight angle with respect to the axis of the lower die, causing the forging force to be applied to only a small area of the workpiece. As one die rotates relative to the other, the contact area between die and workpiece, termed the "footprint," continually progresses through the workpiece, gradually deforming it until a final shape is formed. The tilt angle between the two dies determines the amount of forging force applied to the workpiece. A larger tilt angle results in a smaller footprint; consequently, a smaller amount of force is required to complete the same amount of deformation as compared to a larger contact area. Tilt angles are commonly about 1 to 2°. The larger the tilt angle, however, the more difficult the machine design and maintenance problems are because the drive and bearing system for the tilted die is subjected to large lateral loads and is more difficult to maintain. In addition, a larger tilt angle causes greater frame deflection within the forge, making it difficult to maintain a consistently high level of precision.

Process Advantages. The primary advantage of rotary forging is in the low axial force required to form a part. Because only a small area of the die is in contact with the workpiece at any given time, rotary forging requires as little as one-tenth the force required by conventional forging techniques. The smaller forging forces reduce machine and die deformation and die-workpiece friction. This low level of equipment wear makes rotary forging a precision production process that can be used to form intricate parts to a high degree of accuracy.

The average cycle time for a moderately complex part is 10 to 15 s, which is a relatively short time of deformation from preform to final part. A cycle time in the range of 10 to 15 s yields approximately 300 pieces per hour. The resulting piece is also virtually flash free. Therefore, rotary forging results in a much shorter operation from start to finish.

Tooling costs for rotary forging are often lower than those for conventional forging. The smaller forging forces allow many parts to be cold forged that would conventionally require hot forging, resulting in decreased die wear and greater ease in handling parts after forging.

Machines. Rotary forgers can be broadly classified into two groups. In rotating-die forgers, both dies rotate around their own axis, but neither die rocks or precesses about the axis of the other die. In rocking-die, or orbital forgers, the upper die rocks across the face of the lower die in a variety of fashions. The most common form is where the upper die orbits in a circular pattern about the axis of the lower die. In this case, the upper die can also either rotate or remain stationary in relation to its own axis. Other examples of rocking-die motion include the rocking of the upper die across the workpiece in a straight, spiral, or planetary pattern.

Applications. Rotary forging is generally considered to be a substitute for conventional drop-hammer or press forging. In addition, rotary forging produces parts that would otherwise have to be completely machined because of their shape or dimensions. Currently, approximately one-quarter to one-third of all parts that are either hammer or press forged could be formed on a rotary forge.

Parts made by rotary forging include gears, flanges, hubs, cams, rings, and tapered rollers, as well as thin disks and flat shapes. These parts are axially symmetric and are formed by using an orbital die motion. More complex parts can be forged through the use of such rocking-die motions as straight-line, planetary, and spiral. Straight-line die motion is most commonly used to produce asymmetric pieces, such as T-flanges.

Rotary forging is especially effective in forging parts that have high diameter-to-thickness ratios. Thin disks and large flanges are ideally suited to this process because of the ability of rotary forging to produce a higher ratio of lateral deformation per given downward force than conventional forging. There is also very little friction between the dies. Therefore, the lateral movement of workpiece material in rotary forging is as much as 30% more than that in impact forging.

Rotary forging is also used to produce intricate features on workpiece surfaces. Parts such as gears, hubs, and hexagonal shapes have traditionally been difficult to produce by conventional forging because die-workpiece friction made it difficult to fill tight spots properly on the dies.

Work Materials. Any material, ferrous or nonferrous, that has adequate ductility and cold-forming qualities can be rotary forged. These materials include carbon and alloy steels, stainless steels, brass, and aluminum alloys. In the past, cold-forged production parts were primarily steels with a Rockwell C hardness in the mid 30s or lower. Generally, harder materials should be annealed before forging or should be warm forged.

Warm rotary forging is used for materials with Rockwell C hardness greater than the mid 30s or when an unusually large amount of lateral movement in the workpiece is required. Materials are heated to a point below their recrystallization temperature; for steels, this is generally in the range of 650 to 800 °C (1200 to 1470 °F). Because the working temperature is below the recrystallization temperature, the inherent structure and properties of the metal are preserved.

Warm rotary forging increases forgeability, compared to cold rotary forging. However, some disadvantages are inherent in higher temperature forging. The work-hardening effects on the material that are associated with cold working are not as prominent, even though the working temperature is below the recrystallization temperature. In addition, as with any forging process, higher working temperatures result in increased die wear. Dies not only wear at a faster rate but also must be fabricated from more durable, more expensive materials.

Isothermal and Hot-Die Forging

Hot-die and isothermal forging are special categories of forging processes in which the die temperatures are significantly higher than those used in conventional hot-forging processes. This has the advantage of reducing die chill, thereby producing near-net and/or net shape parts. Therefore, these processes are also referred to as near-net shape, forging processes. These techniques are primarily used for manufacturing airframe structures and jet-engine components made of titanium and nickel-base alloys, but they have also been used in steel transmission gears and other components.

Isothermal Forging

In isothermal forging, the dies are maintained at the same temperature as the forging stock. This eliminates the die chill completely and maintains the stock at a constant temperature throughout the forging cycle. The process uses extremely slow strain rates, thus taking advantage of the strain-rate sensitivity of flow stress for certain alloys.

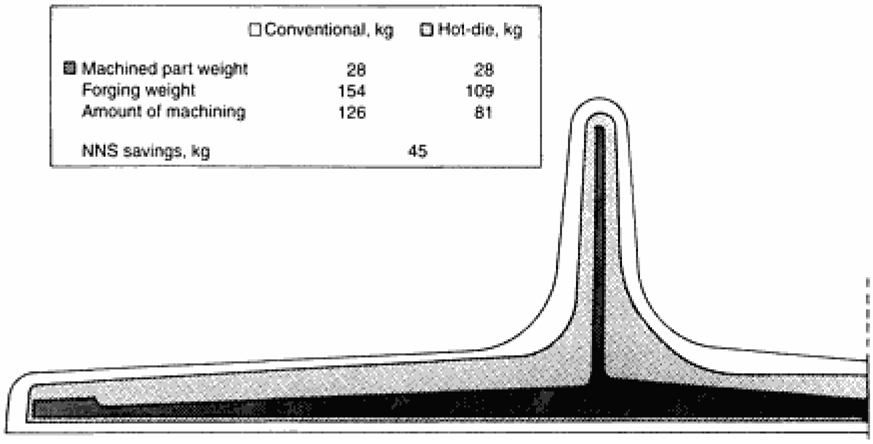
Hot-Die Forging

Hot-die forging is characterized by die temperatures higher than those in conventional forging, but lower than those in isothermal forging. Typical die temperatures in hot-die forging are 110 to 225 °C (200 to 400 °F) lower than the temperature of the stock. When compared with isothermal forging, lower die temperature allows wider selection of die materials, but the ability to produce very thin and complex geometries is compromised.

Process Advantages

The principal criterion for selecting these processes in production is the economic advantage offered because of reduced input material and/or reduced machining. Therefore, they are primarily used for expensive and difficult-to-machine alloys such as titanium and nickel-base alloys.

Reduced Material Costs. These near-net shape processes allow the forging to be designed with smaller corner and fillet radii, a smaller draft angle, and a smaller forging envelope. These design features reduce the additional material incorporated to protect the finished part geometry and therefore reduce the weight of the forging considerably. For costly alloys, the reduction in input weight amounts to a significant cost savings. Figure 28 shows an example of this weight reduction for production of titanium alloy forgings.



	☐ Conventional, kg	▣ Hot-die, kg
■ Machined part weight	28	28
Forging weight	154	109
Amount of machining	126	81
NNS savings, kg	45	

Fig. 28 Comparison of raw material saved in the production of a Ti-6Al-4V structural forging that was hot-die forged versus a conventionally forged part (see cross-sectional areas and legend)

Reduced Machining. Because near-net shape forgings are produced close to end use weight and configuration, less material removal is required during machining when compared with conventional forgings. In most cases, no machining is required, or only finish machining cuts are required to produce the final part. The elimination of complex machining can sometimes justify the use of these processes even for less expensive alloys, as in the case of steel gears forged with net tooth geometry.

Uniformity of Product. The final product produced by isothermal and hot-die forging has more uniform properties because of lower or nonexistent thermal gradients within the forging.

Process Description

In conventional forging operations, the dies are heated to 95 to 205 °C (200 to 400 °F) for hammer operations and to 95 to 425 °C (200 to 800 °F) for press operations. These temperatures are significantly lower than the 760 to 980 °C (1400 to

1800 °F) stock temperature for titanium and the 980 to 1205 °C (1800 to 2200 °F) stock temperature for nickel-base alloys and steels. In addition, these operations are performed at relatively high speeds, resulting in high strain rates. Typical strain rates range to 50 mm/mm per min (50 in./in. per min) for hydraulic presses, 700 mm/mm per min (700 in./in. per min) for screw presses, and exceed 12,000 mm/mm per min (12,000 in./in. per min) for hammers.

For titanium and nickel-base alloys, the flow stress in general is highly sensitive to both temperature and strain rate. Therefore, conventional forging for these alloys is characterized by high resistance to deformation, high forging loads, multiple forging operations, and sometimes cracking.

The isothermal forging and hot-die forging processes overcome some of these limitations by increasing the die temperature close to the temperature of the forging stock. The die temperatures are maintained at these high levels through continuous heating of the dies during the forge operation using induction heating, gas-fired infrared heating, resistance heating, and so on. The heating arrangement is combined with the press so that heat can be provided to the dies during the forging operation. Another heating arrangement uses gas-fired infrared heaters.

Forging Alloys

Alloys forged using these processes include titanium alloys, such as Ti-6A1-4V, Ti-6Al-2Sn-4Zr-2Mo, and Ti-10V-2Fe-3Al, and superalloys, such as Alloy 100, Alloy 95, Alloy 718 (UNS07718), and WASPALOY (Precision Rings, Inc., Indianapolis, IN). In the case of superalloys such as Alloy 100, the working temperature range is so small that the isothermal and hot-die methods are the only feasible forging processes currently available. In addition, at specific temperatures and strain rates, Alloy 100 exhibits superplasticity. When forged within this temperature range and strain rate range, the alloy can be deformed to large strains at low loads and to fairly complex geometries.

Forging Parameters

The same factors that affect conventional forging processes also affect near-net shape processes. However, because of tighter forging designs and the requirements for strict uniformity and consistency, stringent controls on parameters such as forge temperature, strain rate, preform microstructure, forging pressure, and dwell time are all important in deciding the degree of dimensional sophistication and the resultant microstructure of the finished part.

In general, lower strain rates and increased dwell time increase the potential degree of shape complexity and shape sophistication of the forging, but could influence microstructure due to exposure to high temperatures for long periods of time during and after deformation. In addition, very low strain rates cannot be used in hot-die forging because of the potential decrease in the stock temperature. Preform microstructure has a direct influence on the flow stress and superplasticity of the material, sometimes requiring extruded billet with fine-grain structure as the starting material. Some of the alloys that are forged achieve their final mechanical properties by thermomechanical processing; in this case, the selection of the forge temperature and the amount of deformation are controlled by property requirements.

Die Materials

Conventional hot-work die steels do not have adequate strength or resistance to creep and oxidation at near-net shape temperatures. Therefore, expensive nickel-base superalloys or molybdenum alloys (e.g., TZM) must be used. Dies are machined by electrical discharge machining. When TZM is used as a die material, a special atmospheric control with either acuum or inert gases is necessary because of the tendency of molybdenum alloys to oxidize severely at temperatures greater than 425 °C (800 °F).

Precision Forging

Precision forging does not specify a distinct forging process but rather describes a philosophical approach to forging. The goal of this approach is to produce a net shape, or at least a near-net shape, in the as-forged condition. "Net" indicates that no subsequent machining or finishing of a forged surface is required. Thus, a net shape forging requires no further work on any of the forged surfaces, although secondary operations may be required to produce minor holes, threads, and other such details. A near-net shape forging can be either one in which some but not all of the surfaces are net or one in which the surfaces require only minimal machining or finishing. Precision forging is sometimes described as close-tolerance forging to emphasize the goal of achieving, solely through the forging operation, the dimensional and surface finish tolerances required in the finished part.

Usually, precision forging indicates a hot or warm closed-die forging process that has been upgraded to achieve greater process control. Traditionally, hot forging has not been regarded as a precision process. Due to difficulties in producing close tolerances and acceptable surface finish, hot forgings have traditionally been designed with a generous machining allowance sometimes 3 mm ($\frac{1}{8}$ in.) or more. The motivation for precision forging is the elimination, or at least the reduction, of the costs associated with this machining allowance. These costs include not only the labor and indirect costs of the machining and finishing operations but also the cost of the excess raw material that is lost during machining (Fig. 28).

The material cost savings may not be as obvious as the savings obtained by eliminating machining operations. Material costs are a significant fraction (often more than half) of the total cost of a forging. The weight of a traditional forging is often more than twice the weight of the finished part after machining. Given a geometry that is amenable to precision forging, tolerances of ±0.25 mm (±0.010 in.) typically can be held. In many cases, significantly better tolerances have been demonstrated. Forged surfaces have finishes of 3.20 μm (125 μin.) root mean square (rms) or better.

Forging processes discussed under separate headings in this article that are likely to qualify as "precision forging" include close-tolerance, closed-die forgings, warm high-energy-rate forging, radial forging, rotary forging, and hot-die and isothermal forging. Cold-forging processes, such as cold heading and cold extrusion (see the following sections) are traditionally precision processes. Similarly, powder forging processes are also classified as precision forging. Powder forging is described in the Section "Ferrous Powder Metallurgy Materials" in this Volume.

Work metals commonly precision forged include carbon and alloy steels, stainless steels, copper alloys, aluminum alloys, titanium alloys, and nickel-base superalloys. Figure 29 compares precision aluminum forging design characteristics with those of conventional aluminum closed-die forging. Precision aluminum forgings are produced with very thin ribs and webs; sharp corner and fillet radii; undercuts, backdraft, and/or contours; and frequently, multiple parting planes that may optimize grain flow characteristics. Similar improvements are possible in other precision forged metals.

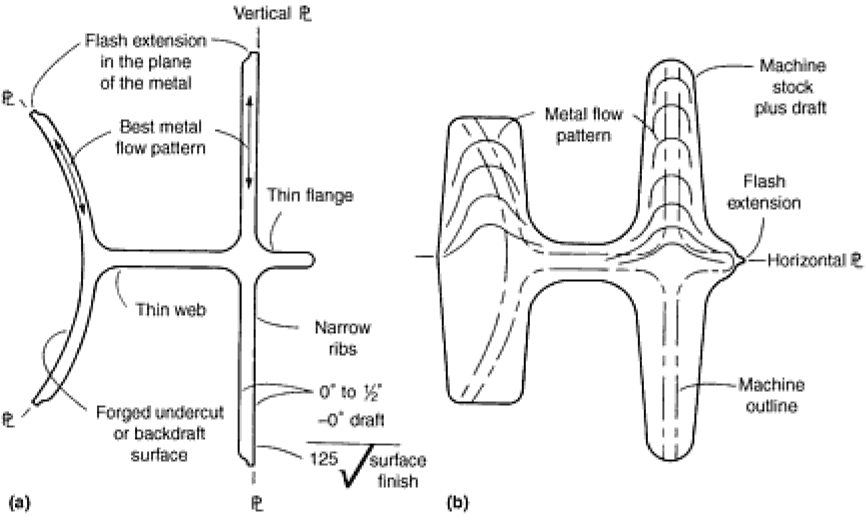


Fig. 29 Cross sections of precision (a) and conventional (b) forgings

Cold Forging

Cold forging is a very general term that covers processes such as coining/sizing, extrusion, and heading/upsetting. The most widely accepted definition of a cold-forging process is the forming or forging of a bulk material at room temperature. What should be emphasized is that in cold forging, no heating (of either the forging stock or the dies) is required for the actual forming operation.

Coining

Coining is a closed-die forging operation, usually performed cold, in which all surfaces of the workpiece are confined or restrained, resulting in a well-defined imprint of the die on the workpiece. It is also a restriking operation, called sizing, that is used to sharpen or change a radius or profile.

Preliminary Workpiece Preparation. Full contact between the blank and die surfaces, which is necessary for coining, usually requires some preliminary meal redistribution by other processes, such as forging or extrusion, because only a small amount of metal redistribution can take place in the coining dies in single-station coining. In progressive-die operations, coining is preceded by other operations such as blanking, drawing, piercing, and bending. Coining is often the final operation in a progressive-die sequence, although blanking or trimming, or both, frequently follow coining.

Development of Detail in the Workpiece. In coining dies, the prepared blank is loaded above the compressive yield strength and is held in this condition during coining. Dwell time under load is important for the development of dimensions in sizing and embossing; it is also necessary for the reproduction of fine detail, as in engraving.

Trimming. Flash that develops during coining and any hangers used to carry the blank through coining, especially in progressive-die coining, must be trimmed from the piece.

Applicability. In coining, the surface of the workpiece copies the surface detail in the dies with dimensional accuracy that is seldom obtained by any other process. It is because of this that the process is used for coin minting.

Decorative items, such as patterned tableware, medallions, and metal buttons are also produced by coining. When articles with a design and a polished surface are required, coining is the only practical production method to use. Also, coining is well suited to the manufacture of extremely small items, such as interlocking-fastener elements. Many automotive components are sized by coining. Sizing is usually done on semifinished products and provides significant savings in material and labor costs relative to machining.

Workpiece Size. Practical limits on workpiece size are mainly imposed by available press capacities and properties of the die material. For example, work metal with a compressive yield strength of 690 MPa (100 ksi) loaded in a press of 22 MN (2500 tonf) capacity can be coined in a maximum surface area of 0.032 m^2 (50 $in.^2$). As the yield strength increases, the area that can be coined using the same press decreases proportionately. However, an increase in strength of the workpiece must be limited so that plastic failure of the die does not occur.

Coining Equipment. In coining, the workpiece is squeezed between the dies so that the entire surface area is simultaneously loaded above the yield strength. To achieve metal deformation, the load determined from the compressive yield strength must be increased three to five times. Because of the area loading requirement and the great stress needed to ensure metal movement, press loading for coining is very severe, frequently approaching the capacity of the equipment used, with consequent danger of overloading.

Some coining equipment, such as drop hammers, cannot be readily overloaded, but presses (especially mechanical presses) can be severely overloaded. This is most likely to happen if more than one blank is fed to the coining dies at a time. Such overloading can break the press and the dies, and it will certainly shorten the life of the dies. Coining can be performed in any type of press that has the required capacity.

Drop hammers and knuckle-type and eccentric-driven mechanical presses are extensively used in coining. High-speed hydraulic presses also are well adapted for coining, especially when progressive dies are used. Large-capacity hydraulic presses are ideal for coining and sizing operations on large workpieces. Conversely, when it is feasible to coin large numbers of small, connected parts, as in a continuous strip of work metal, roll coining is the most economical method.

Die Materials. Tool steels for dies for striking high-quality coins and medals are selected for machinability, hardenability, distortion in hardening, hardness, wear resistance, and toughness. In dies used for decorative coining, materials that can be through hardened to produce a combination of good wear resistance, high hardness, and high toughness are preferred.

A smooth, polished background surface on the die is required for striking proof-type coins and medals. Massive undissolved carbides or nonmetallic inclusions make it more difficult to obtain this smooth background.

Work Materials. Steels that are most easily coined include carbon and alloy grades with carbon content up to approximately 0.30%. Malleable iron castings are frequently sized by coining. Stainless steels of types 301, 302, 304, 305, 410, and 430 are preferred for coining. Free-machining type 303Se (selenium-bearing) is sometimes coined. Types 301, 302, and 430 are used in coining of spoons and forks. Type 305 coins well but is not widely used because of cost. Stainless steels are preferred in the soft annealed condition, in the hardness range of 75 to 85 HRB.

Copper, silver, gold, and their alloys have excellent coinability and are widely used in coin and medallion manufacture. The pure metals are sufficiently soft and coinable to allow extreme deformation in coining, but even after such deformation they are too soft to wear well. As a consequence, important coining metals are prepared by alloying; thus, a relatively wide range of hardness is obtainable.

Cold Heading

Cold heading is a cold-forging process in which the force developed by one or more strokes (blows) of a heading tool is used to upset (displace) the metal in a portion of a wire or rod blank in order to form a section of different contour or, more commonly, of larger cross section than the original. The process is widely used to produce a variety of small- and medium-sized hardware items, such as bolts and rivets. Cold heading, however, is not limited to the cold deformation of the ends of a workpiece nor to conventional upsetting; metal displacement can be imposed at any point, or at several points, along the length of the workpiece and may incorporate extrusion in addition to upsetting. In cold heading, the cross-sectional area of the initial material is increased as the height of the workpiece is decreased. Advantages of the process over machining of the same parts from suitable bar stock include:

- Almost no waste material
- Increased tensile strength from cold working
- Controlled grain flow

Suitable Work Metals. Most cold heading is done on low-carbon steel wire with hardness ranging from Rockwell B 75 to 87. This is the type of material for which most machines are rated. Copper, aluminum, stainless steel, and some nickel alloys are also cold headed. Titanium, beryllium, magnesium, and refractory metals are less formable at room temperature and are likely to crack when cold headed; these metals are sometimes warm headed.

Rating Formability. Metals and alloys are rated for cold heading on the basis of the length of stock, in terms of diameter, that can be successfully upset. Equipped with flat-end punches, most cold-heading machines can upset to approximately two diameters of low-carbon steel wire per stroke. If the unsupported length is increased beyond approximately two diameters, the stock is likely to fold onto itself, as shown in Fig. 30. For more formable metals, such as copper and some copper alloys, the length of upset per stroke may be up to four diameters. Punches and dies can, however, be designed to increase the headable length of any work metal. For example, with a coning punch (Fig. 31) or a bulbing punch, it is possible to head as much as six diameters of low-carbon steel stock in two strokes.

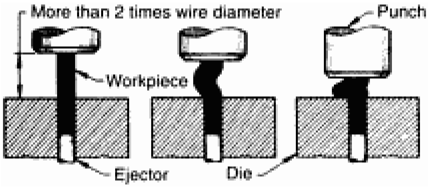


Fig. 30 Typical folding effect with a flat-end punch when heading low-carbon steel wire with unsupported length of more than two diameters

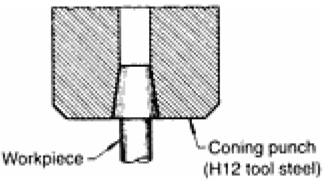


Fig. 31 Use of a coning punch in the first blow of a two-blow heading operation, which enables a low-carbon steel workpiece to be upset to a length of up to six diameters in two strokes

Machines. Standard cold headers are classified according to whether the dies open and close to admit the work metal or are solid, and according to the number of strokes (blows) the machine imparts to the workpiece during each cycle. The die in a single-stroke machine has one mating punch; in a double-stroke machine, the die has two punches. The two punches usually reciprocate so that each contacts the workpiece during a machine cycle.

Tools used in cold heading consist principally of punches or hammers and dies. The dies can be made as one piece (solid dies) or as two pieces (open dies), as shown in Fig. 32.

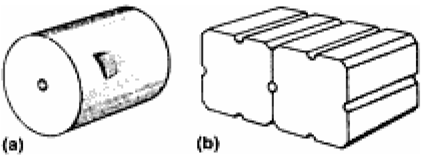


Fig. 32 Solid (one-piece) and open (two-piece) cold heading dies. (a) Solid die. (b) Open dies

Solid dies (known also as closed dies) consist of a cylinder of metal with a hole through the center (Fig. 32a). Solid dies can be made entirely from one material or may be made with the center portion surrounding the hole as an insert of a different material.

Open dies (also called two-piece dies) consist of two blocks with matching grooves in their faces (Fig. 32b). When the grooves in the blocks are put together, they match to form a die hole as in a solid die. The die blocks have as many as eight grooves on various faces, so that as one wears, the block can be turned to make use of a new groove.

Tool Materials. The shock loads imposed upon cold heading tools must be considered in selecting tool materials. For optimum tool life it is essential that both punches and dies have hard surfaces (preferably Rockwell C 60 or higher). However, with the exception of tools for cold heading of hard materials, the interior portions of the tools must be softer (Rockwell C 40 to 50, and sometimes as low as Rockwell C 35 for larger tools) or breakage is likely.

To meet these conditions, shallow-hardening tool steel such as W1 or W2 is used extensively for punches and open dies and for solid dies made without inserts.

Lubrication. Although some of the more ductile metals can be successfully cold headed to moderate severity without a lubricant, most metals to be cold headed are lubricated to prevent galling of the work metal or the dies, sticking in the dies, and excessive die wear.

Lubricants used include lime coating, phosphate coating, stearates and oils, and plating with softer metals such as copper, tin, or cadmium.

The ultimate in lubrication for steel to be cold headed is a coating of zinc phosphate with stearate soap--the same as is used for cold extrusion of steel.

Cold Extrusion

Cold extrusion is so called because the slug or preform enters the die at room temperature or at a temperature appreciably below the recrystallization temperature. Any subsequent rise in temperature, which may amount to several hundred degrees Fahrenheit, is caused by the thermomechanical effects of plastic deformation and friction. Cold extrusion involves backward or forward, or combined backward-and-forward, displacement of metal by plastic flow under steady, though not uniform, pressure. Backward displacement from a closed die is in the direction opposite to punch travel, as shown in Fig. 33(a). Workpieces are often cup-shaped and have wall thickness equal to the clearance between the punch and die. In forward extrusion, the work metal is forced in the direction of the punch travel, as shown in Fig. 33(b). Sometimes these two basic methods of extrusion are combined so that some of the work metal flows backward and some forward, as shown in Fig. 33(c).

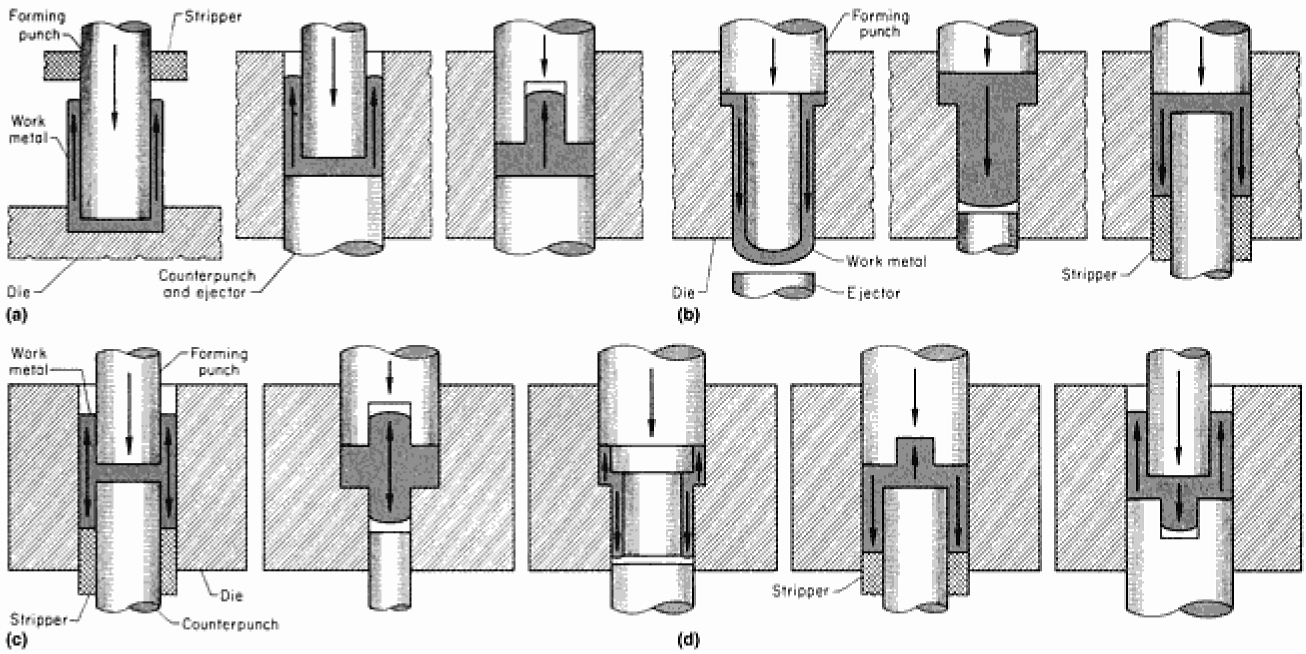


Fig. 33 Displacement of metal in cold extrusion. (a) Backward. (b) Forward. (c) Combined backward and forward

Metals Cold Extruded. Aluminum and aluminum alloys, copper and copper alloys, low-carbon and medium-carbon steels, modified carbon steels, low-alloy steels, and stainless steels are the metals most commonly cold extruded. This listing is in the order of decreasing extrudability.

Extrusion ratio *R* is determined by dividing the original area undergoing deformation by the final deformed area of the workpiece:

$$R = \frac{A_0}{A_f}$$

Because volume remains constant during extrusion, the extrusion ratio can also be estimated by increase in length. An extrusion ratio of 4 to 1 indicates that the length has increased by approximately a factor of four.

The metal being extruded has a large effect on the maximum ratio that is practical. Some typical approximate maximum extrusion ratios are 40 for aluminum alloy 1100, 5 for 1018 steel, and 3.5 for type 305 stainless steel and similar austenitic grades.

Extrusion pressure increases with extrusion ratio. Figure 34 shows that extrusion ratio has a larger effect on ram pressure in the forward extrusion of carbon steel than either carbon content or type of annealing treatment. Figure 35 illustrates the effect of tensile strength on extrudability in terms of ram pressure for both the backward and forward extrusion of low-carbon and medium-carbon steels of the 1000, 1100, and 1500 series at different extrusion ratios.

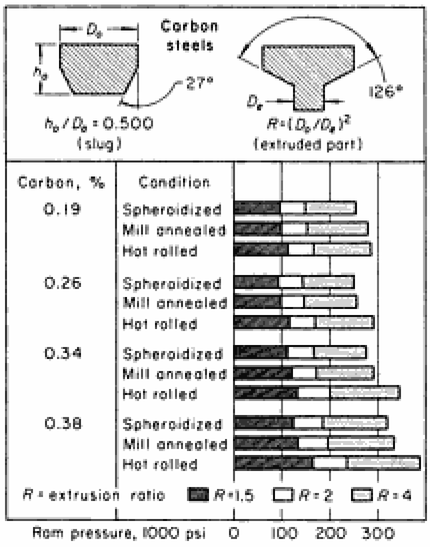


Fig. 34 Effect of carbon content, type of annealing treatment, and extrusion ratio on maximum ram pressure in forward extrusion of the carbon steel part shown from the preformed slug shown

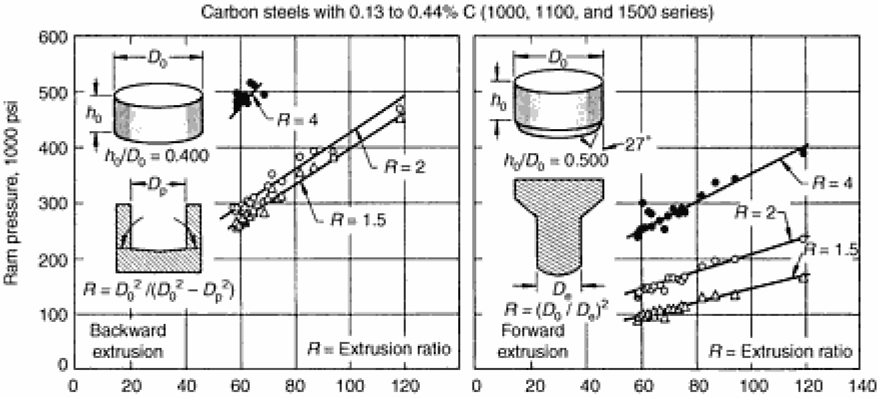


Fig. 35 Effect of tensile strength of steel being extruded on ram pressure required for backward and forward extrusion at different ratios

Presses and Headers. Hydraulic presses, mechanical presses, special knuckle-joint presses for cold extrusion, special cold forging machines, and cold heading machines are employed for cold extrusion. Most presses used for cold extrusion are essentially the same as those used for sheet metal forming.

Most cold extrusion operations are performed on mechanical presses or cold heading machines. Of the two, mechanical presses are used more often because of their adaptability to other types of operations. Mechanical presses are generally less costly and are capable of higher speeds than are hydraulic presses of similar capacity.

The ram pressure that must be borne during the stroke is a function of the workpiece strength (as affected by composition, state of cold work, anneal, etc.) and the extrusion ratio, as shown in Fig. 34 and 35.

Tooling. The components of a typical tool assembly used for backward extrusion of steel parts are identified in Fig. 36. There is considerable variation in tooling practice and in the design details of tool-assembly components.

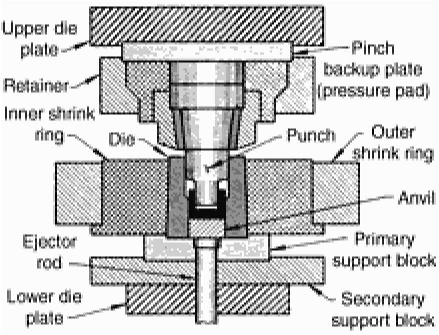


Fig. 36 Nomenclature of tools comprising a typical setup for backward extrusion

Tool Materials. Compressive strength of the punch and tensile strength of the die are important considerations when selecting material for cold extrusion tools. Because the die is invariably prestressed in compression by the pressure of the inner and outer shrink rings, the principal requirement for a satisfactory die is a combination of tensile yield strength and prestressing that will prevent failure. Punches must have enough compressive strength to resist upsetting without being hazardously brittle. Thus, almost without exception, and particularly for extruding steel, the primary tools in contact with the workpiece must be made of steels that will harden through the section in the sizes involved. (This is notably different from cold heading tools, for which a hard case and soft core are usually desired.) Among the relatively few exceptions are small dies made of a water-hardening tool steel and bore quenched. As the bore hardens, the remainder of the die cools and shrinks, placing the bore in compression.

The degree of strength required for the tools is influenced by workpiece shape, composition and hardness of the metal being extruded, and production requirements.

Preparation of Slugs. Despite the loss of metal, sawing and cutting off in a machine, such as an automatic bar machine, are widely used methods of producing slugs. The advantages of these methods include dimensional accuracy, freedom from distortion, and minimal work hardening. Shearing is an economical means of producing slugs. Variation in the sizes of the slugs is a major disadvantage of shearing. If slugs are allowed to vary in size, die design must allow for the escape of excess metal in the form of flash. An alternative to die adjustment in some applications is to compensate for the distortion and other discrepancies in sheared slugs by coining the slugs to desired dimensions.

Lubricants for Steel. In most instances, the starting metal surface is given a conversion coating such as zinc phosphate to facilitate lubrication. A soap lubricant gives best results. Slugs are immersed in a dilute (45 to 120 kg/m^3, or 16 oz/gal) soap solution at 60 to 90 °C (145 to 190 °F) for three to five minutes. Some soaps are formulated to react chemically with a zinc phosphate coating, resulting in a layer of water-insoluble metal soap (zinc stearate) on the surfaces of the slugs. This coating has a high degree of lubricity and maintains a film between the work metal and tools at the high pressures and temperatures developed during extrusion.

Other soap lubricants, such as high-titer sodium tallow soaps, with or without filler additives, can be used effectively for mild extrusion of steel. This type of lubricant is absorbed by a phosphate coating, rather than reacting with it.

Although the lubricant obtained by reaction of soap and zinc phosphate is best for extruding steel, its use demands precautions. If soap builds up in the dies, workpieces will not completely fill out. Best practice is to vent all dies so that the soap can escape and also to keep a coating of mineral seal oil (applied as an air-oil mist) on the dies to prevent adherence of the soap.

When steel extrusions are produced directly from coiled wire (similar to cold heading), the usual practice is to coat the coils with zinc phosphate. This practice, however, has one deficiency; because only the outside diameter of the work metal is coated, the sheared ends are uncoated at the time of extrusion. This deficiency is partly compensated for by constantly flooding the work with sulfochlorinated oil.

Lubricants for Aluminum. Aluminum and aluminum alloys can be successfully extruded with lubricants such as high-viscosity oil, grease, wax, tallow, and sodium-tallow soap. Zinc stearate, applied by dry tumbling, is an excellent lubricant for extruding aluminum.

The lubricant should be applied to clean metal surfaces, free from foreign oil, grease, and dirt. Preliminary etching of the surfaces increases the effectiveness of the lubricant.

For the most difficult aluminum extrusions (less extrudable alloys or greater severity, or both), the slugs should be given a phosphate-treatment followed by application of a soap that reacts with the surface to form a lubricating layer similar to that formed when extruding steel.

Impact extrusion, often simply called impacting, is similar to backward, forward, and combination extrusion except that faster speeds, shorter strokes, and shallower dies are employed. Cold impacting is used extensively for the easy extrusion of nonferrous metals having low melting points and good ductility, such as lead, tin, zinc, aluminum, copper, and alloys of these metals.

Hot Extrusion

Hot extrusion involves pushing a heated billet of metal through a die. The temperature at which extrusion is performed depends on the material being extruded (Table 3). The extruded product can be hollow or solid, and the cross section can vary from a simple round to a complicated shape. Direct (forward) extrusion, wherein the metal is forced under pressure through a die opening of the desired cross-sectional area and shape, is most widely employed. The die is located in the end of the cylinder opposite the ram. In the less-used indirect (backward) extrusion process, the die is mounted on a hollow ram and is pushed through the metal instead of the metal being pushed through the die. The principal differences between direct and indirect extrusion are illustrated in Fig. 33.

Table 3 Typical billet temperatures for hot extrusion

Material	Billet temperature	
	°C	**°F**
Lead alloys	90-260	200-500
Magnesium alloys	340-430	650-800
Aluminum alloys	340-510	650-950
Copper alloys	650-1100	1200-2000
Titanium alloys	870-1040	1600-1900
Nickel alloys	1100-1260	2000-2300

Process Variations

The three basic types of hot extrusion are nonlubricated, lubricated, and hydrostatic (Fig. 37).

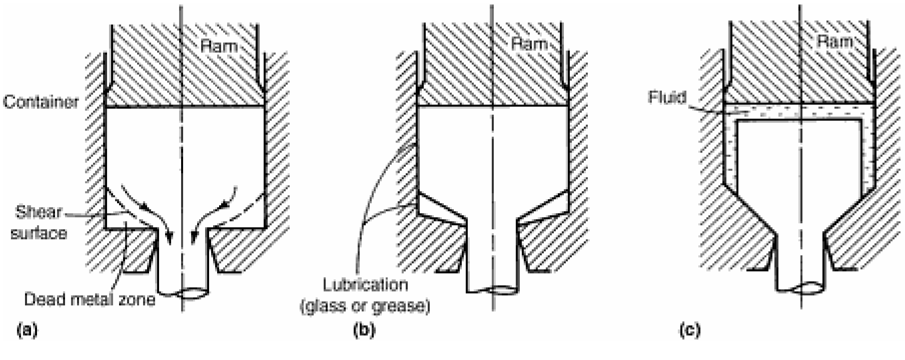


Fig. 37 Schematics of the (a) nonlubricated, (b) lubricated, and (c) hydrostatic extrusion processes

Nonlubricated Hot Extrusion. As the name implies, this extrusion method uses no lubrication on the billet, container, and die, and it can produce very complex sections, with mirror surface finishes and close dimensional tolerances. Generally, aluminum alloys are extruded without lubrication.

In lubricated hot extrusion, a suitable lubricant (usually ground or powdered glass or grease) is placed between the extruded billet and the die. The choice between grease and glass lubricants is based mainly on extrusion temperature. Below 1000 °C (1830 °F), grease lubricants are used; above this temperature glass is employed. Steels, titanium alloys, nickel alloys, and copper alloys require a lubricant during extrusion.

In hydrostatic extrusion, a fluid film present between the billet and die exerts pressure on the deforming billet. The hydrostatic extrusion process is primarily used when conventional lubrication is inadequate--for example, in the extrusion of brittle alloys (including beryllium and TZM molybdenum), composites, or clad materials. For all practical purposes, hydrostatic extrusion can be considered an extension of the lubricated hot extrusion process.

Presses and Tooling for Hot Extrusion

Horizontal and vertical presses are used for hot extrusion. Horizontal presses are the most common (Fig. 38). Most modern extrusion presses are driven hydraulically, but mechanical drives are used in some applications, such as the production of small tubes. Two basic types of hydraulic drives are available: direct and accumulator. In the past, accumulator presses were the most widely used, but today direct-drive presses are used more extensively.

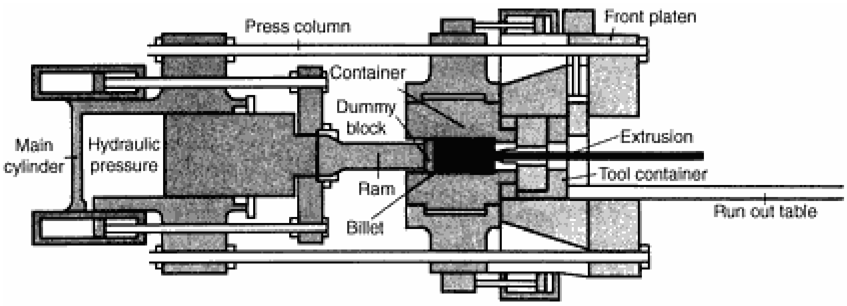


Fig. 38 Schematic of a horizontal extrusion press showing a hydraulically powered ram forcing the heated billet through the die

The container, which receives the hot billet to be extruded, is a heated cylinder that is almost always fitted with a liner. The liner must resist the abrasive action of the billet during extrusion and should maintain relatively high hardness at elevated temperatures. The container and liner should be made of materials with high fracture toughness and good resistance to low-cycle fatigue.

The ram, also referred to as the stem, operates within the liner and transmits pressure from the press cylinder to the billet. The ram must sustain high cyclic compressive loading. The material used for the ram should have good resistance to upsetting, work hardening, thermal shock, and rapidly applied stress.

The dummy block is a block of steel that is inserted between the ram and the billet to absorb the heat and erosion that otherwise would be imposed directly on the ram. The dummy block should resist indentation by the billet at temperatures approaching the billet temperature.

The die or die assembly is the area through which the billet is pushed to form the extruded bar or shape. A die assembly typically consists of the following component parts (see Fig. 39):

- A die, which is usually a circular steel block with a cut pattern of the transverse section of the shape to

be produced
- A die ring (die holder), which is a steel ring located in front of the container that contains the die and the backer
- A die backer, which is a circular steel block placed behind an extrusion die for support. The hole in the backer is slightly larger than the hole in the die to allow for clearance of the extrusion.
- One or more bolsters, which are circular steel blocks used adjacent to the backer to reinforce the die and backer against billet pressure
- A tool carrier (die slide or housing)

The die itself must have high toughness combined with resistance to wear and softening at elevated temperatures. The other components of the die assembly should be high in both strength and toughness.

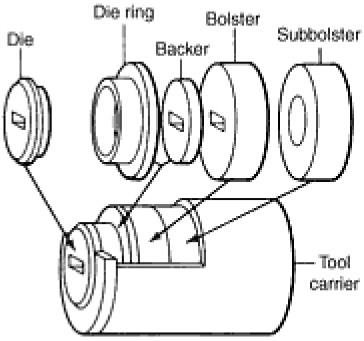


Fig. 39 Typical extrusion die assembly, showing relative positions of components in a tool carrier

The mandrel is a rod used to produce the cavity in a hollow shape while it is being extruded. Mandrels should be high in hot hardness, abrasion resistance, fracture toughness, and yield strength.

Press Operation. With the ram retracted, a hot billet or slug is placed in the container. A dummy block is inserted between the ram and billet; then the hot billet is pushed into the container liner and advanced under high pressure against the die. The metal is squeezed through the die opening, assuming the desired shape, and is severed from the remaining stub by sawing or shearing.

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Powder Metallurgy

Erhard Klar, Consultant

Introduction

POWDER METALLURGY (P/M) is a small but important branch of metallurgy that comprises the manufacture of metal powders and articles from powders through forming and sintering. In its most basic and widely used form, it consists of pressing a powder to the desired shape, followed by heating at an elevated temperature below its melting point.

The beginning of modern P/M is attributed to Wollaston (Ref 1) who, early in the 19th century, described a press-sinter forging technique for making fully dense platinum, a metal which, at that time, could not be melted because of its high melting point. Early in the 20th century, high melting point metals like tungsten and molybdenum were formed by P/M processing into articles for the electrical industry.

Powder metallurgy processing was also used for the manufacture of composite electrical contacts. Cemented carbides and porous bronze bearings followed in the 1920s, friction materials in the 1930s, and several refractory metals and so-called structural parts in the 1940s. The latter application evolved parallel to the growth of the automotive industry, and, to the present day, overall use of powder metallurgy in fully industrialized countries is strongly dependent on the automotive industry (Fig. 1).

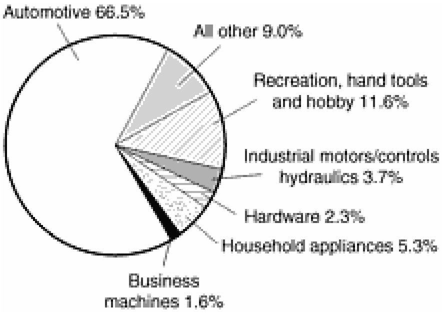

Fig. 1 Powder metallurgy parts markets for North America, 1995. Source: Metal Powder Industries Federation

In the 1950s and 1960s the structural parts segment of the P/M industry expanded toward higher and full density processes and products. This led to increasing competition of the P/M industry with wrought metals. Examples of this evolution include powder forged steels, hot isostatically pressed tool steels, nickel-base superalloys, and high specific stiffness aluminum aircraft alloys

Although early uses were based on the ability of P/M to form articles of high melting point metals without melting and, later, to produce unique structures such as porous oil-impregnated bearings and composite materials, the success of the structural parts segment of P/M is largely based on economic advantages. These include energy efficient, environmentally acceptable, and nearly scrap-free mass production of parts by pressing and sintering, often without any subsequent machining or other secondary treatments.

Powder metallurgy is a dynamic technology. Advances in powder making, new processing equipment, and new P/M processes continue to emerge. Over the years, many variants of the basic compaction and sintering process have been developed. In addition to new and stronger alloys, the high and full density processes (i.e., warm compaction, hot isostatic pressing, powder forging, powder injection molding, powder rolling, and powder extrusion) combined with excellent control of microstructure and the innate capability of P/M to produce composite materials, allow the manufacture of conventional and unique materials possessing a wide property spectrum of the highest quality.

In spite of the many attractive attributes of P/M, there are limitations The basic and economic press-and-sinter technique, employing mechanical and hydraulic presses for the compaction of the powders, has shape and size limitations. Because of the generally higher cost of powders in comparison to ingots and the high cost of tooling, presses, and sintering furnaces, the manufacture of large part numbers, at least 1,000 to 10,000, is usually essential if competition with alternate manufacturing processes, such as machining, die and investment casting, die forging, fine blanking, and stamping, is to be successful.

This explains the preferred use of P/M in industries requiring large part numbers, especially the automotive industry. Manufacturing processes ("freeform powder molding") that allow for the production of small lot sizes of P/M components without resorting to expensive hand tooling are under development (Ref 2).

Figure 2 shows total metal powder shipments of iron, copper and copper alloys, and stainless steel powders in North America back to their initial uses. The high initial growth rate of iron powders slowed down to a more sustainable annual rate of approximately $3\frac{1}{2}$% around 1970, a rate only moderately higher than the U.S. gross domestic product. This is related in part to the still increasing usage of P/M parts in the automobile. The compound annual growth rate of stainless steel powders and parts is still around 5%. This is attributed to improvements in the corrosion resistance of sintered stainless steels and their uses in more demanding applications such as in antilock brake system (ABS) sensor rings and automobile exhaust system components. The growth rate of copper powders, because their consumption was recorded in the 1940s and 1950s, exhibits a stagnant consumption over the past 50+ years. This is attributed largely to the relatively high cost and price volatility of copper and its partial or full substitution with less expensive materials such as iron and plastics.

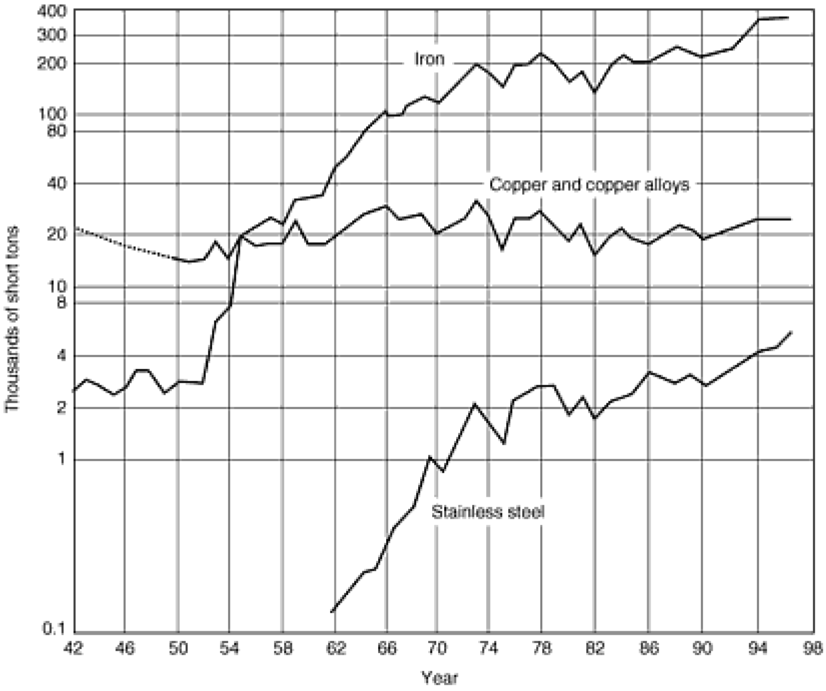

Fig. 2 Powder production in North America. Source: Metal Powder Industries Federation

In the following, some basic P/M terms are briefly explained, and after a discussion of powder properties, an overview of general and individual powder production processes is presented. Consolidation of powders by pressing and sintering as well as high density methods are treated similarly. Emphasized are distinguishing features of powders, their manufacturing processes, compacting processes, and consolidated part properties. This information forms a basis for selecting the optimum P/M approach in the design of a product. Actual properties of P/M parts are found in the Sections dealing with the individual alloy product classes in this Handbook.

For more details, refer to *Powder Metal Technologies and Applications,* Volume 7, *ASM Handbook,* 1998; to general textbooks on P/M (Ref 3 and 4); and to the Selected References listed at the conclusion of this Section.

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P/M Definitions

Definitions of key powder metallurgy terms, which are used in the following sections, are given here. Additional terms related to P/M technology can be found in the "Glossary of Metallurgical and Metalworking Terms" in this Handbook.

- **activated sintering**
  - A sintering process in which the rate of sintering is increased, for example by addition of a substance to the powder
- **apparent density**
  - The weight of a unit volume of powder. It is related to particle shape; the more irregular the shape of a powder particle, the lower the apparent density.
- **cold isostatic pressing**
  - The densification of a material under isostatic pressure conditions at room temperature using a flexible mold and a high pressure hydrostatic pressure in a hydraulic chamber
- **compressibility**
  - A measure of the ability of a powder to densify under pressure
- **cross contamination**
  - Contamination of a material with material of a different (chemical) composition as a result of the (sequential) manufacture of different materials using the same processing equipment
- **dimensional change**
  - The shrinkage or growth of a part as a result of sintering
- **double-action pressing**
  - Method by which a powder is pressed in a die between two punches moving from opposite directions into the die cavity
- **flow rate**
  - The time required for a powder sample of standard weight to flow through an orifice in a standard instrument according to a specified procedure
- **green part**
  - The pressed part
- **green strength**
  - A measure of the ability of a green (i.e., pressed) compact to maintain size and shape during handling prior to sintering
- **hot isostatic pressing**
  - A process combining temperature and high pressure gas to densify a material into a net-shape component using a pressure-tight outer envelope
- **metal injecting molding**
  - A process in which a mixture of a metal powder and plastic binder is injection molded
- **powder forging**
  - Hot densification by forging of an unsintered, presintered, or sintered preform made from powder (also known as P/M forging or known as P/M hot forming)
- **powder metallurgy**
  - The branch of metallurgy related to the manufacture of metal powders and articles fabricated from powders by the application of forming and sintering processes
- **preform**
  - A compact blank intended to be subjected to deformation and densification involving change of shape.
- **premix**
  - A lubricated powder mixture ready for compaction

- **prior particle boundaries**
    - Precipitates present on the surfaces of powder particles, or precipitates forming on the surfaces during processing. These boundaries are usually visible by metallography and responsible for low ductility and deterioration of other properties of parts made from such powders.
- **punch**
    - Part of a die or compacting tool set that is used to transmit pressure to the powder in the die cavity
- **single-action pressing**
    - Method by which a powder is pressed in a stationary die between one moving and one fixed punch
- **sintering**
    - The bonding of neighboring particles in a mass of powder (as in a compact) by heating
- **withdrawal process**
    - Operation by which a die descends over a fixed lower punch to free the compact

Powder Characteristics

For a powder to be suitable to P/M processing, it must possess powder properties that are tailored to the particular compacting and sintering process used, and it must provide the end or performance properties required in the finished P/M part. It must also be cost effective and, increasingly, powder specifications are becoming stricter and narrower in the interest of improving quality and consistency of P/M parts. The most significant fundamental powder characteristics include particle size, particle size distribution, particle shape, and purity of a powder. Engineering-type powder properties such as apparent density, flow rate, green strength, and compressibility depend on several of the fundamental powder properties in a more complex way. Quantitative relationships between the two types of properties are still of an empirical nature.

Particle Size. Powders suitable for conventional P/M processing are typically called -80 mesh powders, that is, powders with an upper particle size of approximately 177 μm. This upper particle size limit arises from the need of porous sintered parts to have a surface texture that is pleasing to the eye and to assure adequate mechanical properties. Also, many powders are mixtures of several components that alloy with each other during sintering by solid-state diffusion. In the presence of large particles, the sintering times of such systems would be unacceptably long.

The lower end of the particle size spectrum of typical P/M powders is approximately 1 μm. Most P/M powders have -325 mesh (<44 μm) fractions not exceeding 30 to 40%. These requirements are dictated by the need of a powder to flow freely, or by gravity, from a storage hopper to the die in an automated compacting press. With decreasing particle size, increasing amounts of fines (-325 mesh), and with more irregular particle shapes, powder flowability deteriorates. Moderate amounts of fines also provide for a good balance between sintering activity and shrinkage during sintering. In contrast to injection molding, which uses fine powders for rapid sintering and maximum densification (shrinkage), conventional pressing and sintering seeks to minimize shrinkage in the interest of maintaining dimensional tolerances.

Particle Size Distribution. In between these limits of coarse and fine, most P/M powders have particle size distributions consisting of more or less evenly weighted intermediate size powder fractions in accordance with the particulars of a powder production process. For most P/M uses the actual numbers of these fractions are of lesser importance than their consistency from powder lot to powder lot.

Lubricants. Powders used in the press-and-sinter process typically contain $\frac{1}{2}$ to $1\frac{1}{2}$% of an admixed lubricant with a function that is to reduce friction during pressing, thereby facilitating compacting and ejection and lengthening the useful life of a compaction die. Widely used lubricants include stearic acid, synthetic waxes, zinc stearate, lithium stearate, and mixtures of these. The addition of a lubricant to a powder affects many of its engineering properties, including powder flow, apparent density, green strength, and compressibility. Lubricant optimization usually consists of identifying, empirically, composition and amount of lubricant providing the smallest loss of green strength for a given reduction in friction. Lubricants volatilize and decompose during sintering.

Coarse and Fine Powders. Some P/M processes employ finer or coarser powders than those used in conventional pressing and sintering. Powder injection molding (PIM) works best using powders with particle sizes up to approximately 20 μm. The small powder particles, with high specific surface areas, provide the increased driving force for shrinkage during sintering to achieve nearly full density required in this process. The problem of powder flow is solved by compounding the fine powder with the organic binder into a coarser-grained, flowable powder.

Powders containing particles exceeding 177 μm are sometimes used in powder forging, hot isostatic pressing, and powder extrusion. These processes typically produce fully dense materials, and, therefore, some of the restrictions that apply to porous materials do not apply.

Particle Shape. Another important distinction of metal powders relates to particle shape, or more broadly, particle morphology. Particle shape often reveals the process by which a powder was manufactured. Particle morphology greatly affects flow, apparent density, compressibility, and sintering characteristics of a powder. In the basic press-and-sinter process a powder needs to possess sufficient green strength to permit safe handling of the green compact prior to sintering. Spherically shaped powders have the lowest green strength characteristics and for that reason are generally not usable for room temperature die compaction. Conversely, such powders are often preferred in other P/M processes (i.e., hot isostatic pressing, powder extrusion, and powder injection molding) because of their higher packing and filling densities and their lower oxygen contents.

For thin or fragile parts, high green strength powders are preferred. Copper powders used in P/M friction products are an example where green strength has been driven to an extreme and where special powder manufacturing processes have been developed. Here, the need for high green strength derives from the fragile shape of some friction parts and the presence of other materials for which copper forms the supporting matrix. The more irregular the shape of the copper particles, the less copper is required to form a coherent matrix for holding the other components. The preferred friction grade copper powders are of small particle size, high specific surface area, and high purity. All three properties contribute to high green strength. These requirements explain why copper powders produced by hydrometallurgy, electrolysis, and oxide reduction are suitable for high green strength applications, whereas atomized copper powders are not. The inability of these powders to flow is not important because the copper powder is mixed with several other powders that are coarse enough so that the final powder mixture flows, or special powder dispensers are used to facilitate uniform die filling, even though the powders are not free flowing.

Compressibility and Green Strength. Since its beginning in the 1940s, the structural parts industry has placed great emphasis on the compressibility of a powder. A more compressible powder can be compacted to a higher density and, consequently, permits the manufacture of parts possessing higher mechanical properties, or a more compressible powder permits the use of a smaller and less expensive compaction press. Figure 3 shows typical compressibility curves for aluminum, copper, and iron powders. Maximizing compressibility is of particular importance for relatively hard powders that require high compaction pressures such as iron, tool steel, and stainless steel powders. Both compressibility and green strength of these powders improve by decreasing their hardness through minimizing the concentration of interstitials (carbon, nitrogen, and oxygen), through the removal of work hardening by annealing and by assuring, through proper heat treatment, the absence of any hard phases. Figure 4 shows the large negative effects of residual carbon in iron powder on compressibility and green strength. It is equally important for stainless steel powders.

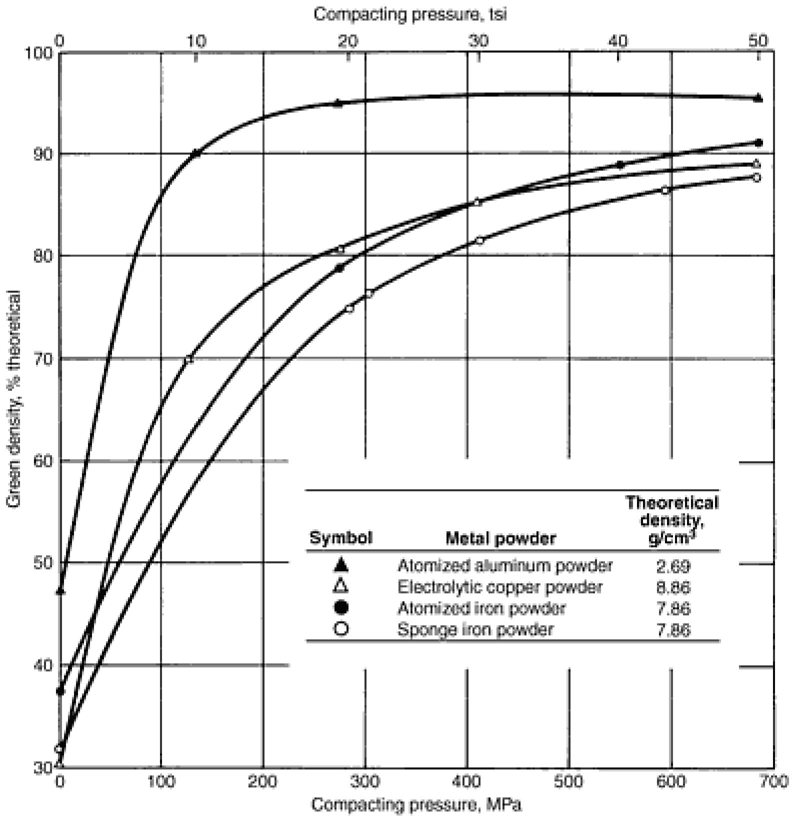

Fig. 3 Compressibility curves for various metal powders. Source: Ref 5

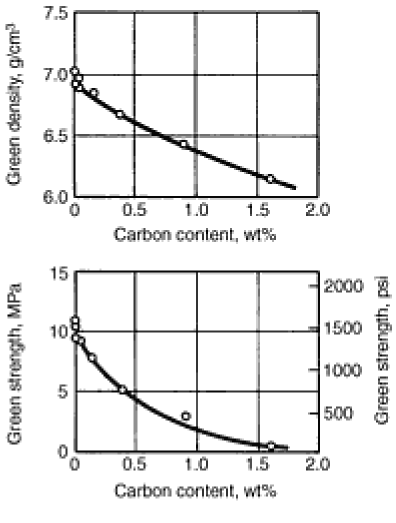

Fig. 4 Effect of residual carbon content on compressibility and green strength of water-atomized high carbon iron. Pressed at 550 MPa (40 tsi) with 1% zinc stearate admixed. Symbols represent experimental data points. Source: Ref 5

In terms of morphological powder characteristics, a compromise must be sought between compressibility and green strength as the factors that improve compressibility have the opposite effect on green strength. The correct and optimum balance for high compressibility is to tailor the morphological characteristics of a powder so that green strength is just sufficient for the intended use. Compressibility increases and green strength decreases with decreasing surface area and increasing particle size of a powder. This explains why the highest compressibility iron powders available today are atomized powders of very low interstitial contents, of high apparent density with nonporous solid particles, and with moderate amounts (approximately 20%) of fines (-325 mesh). The detrimental effect of sponge powders, possessing internal particle pores, on compressibility is illustrated in Fig. 5(a). Figure 5(b) shows the positive effect of particle porosity on green strength. Typical green strength curves for a low-alloy steel powder are shown in Fig. 6.

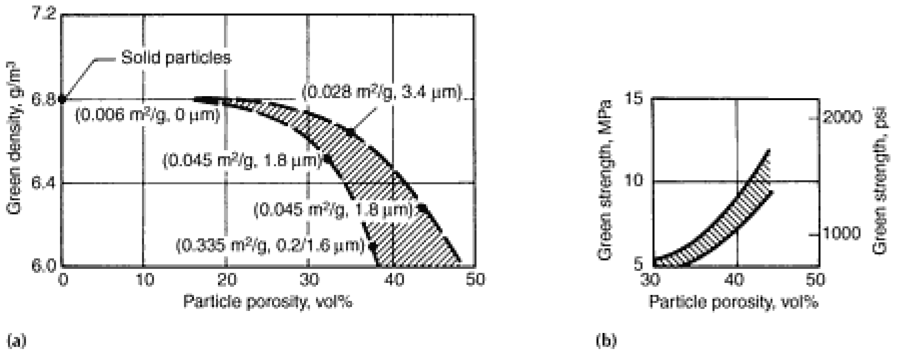

Fig. 5 Effect of particle porosity on (a) green density and (b) green strength of solid and porous iron powders. Powders were pressed at 414 MPa (30 tsi) using die wall lubrication. The figures in parentheses in (a) signify specific surface areas (as measured by the gas adsorption method) and average intraparticle pore sizes of powders. Source: Ref 5

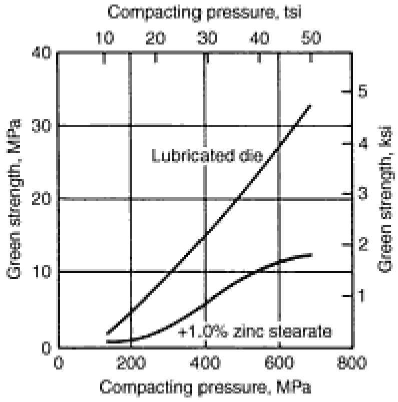

Fig. 6 Effect of admixed lubricant on green strength of water-atomized 4600 low-alloy steel powder. Source: Ref 5

Powder Cleanliness. Powder cleanliness in P/M has become of increasing importance during the past 30 years. It generally refers to the presence of foreign, unreducible oxides and metallic trace impurities. It also includes the presence of foreign nonmetallic material arising from cross contamination. Soluble trace impurities reduce the electrical and thermal conductivities of copper; unreducible oxides can interfere with sintering and seriously impair the dynamic mechanical properties of high density parts, even at very low concentrations. For P/M products made by pressing and sintering, the density is typically below approximately 92% of theoretical. At such densities, the pores of a part usually overshadow the effect of oxidic impurities as stress raisers. It is for this reason that sponge iron powders with their larger amounts of unreducible oxides continue to be used successfully in the manufacture of low and medium density parts, whereas with the appearance of high and full density P/M processes, special "forging grade" iron powders were developed that contain only minimal amounts (and of small particle size) of unreducible inclusions. Figure 7 illustrates the large effect of oxide inclusions upon the toughness of a fully dense 4340 steel. Tool steel, and even more so superalloy powders, are produced with still greater care in order to minimize defects in the consolidated products.

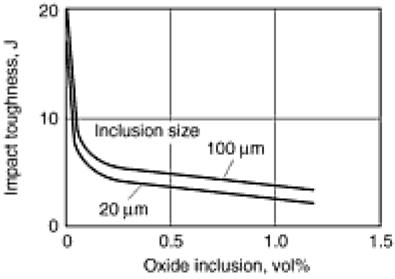

Fig. 7 Effect of oxide inclusions on impact toughness of fully dense 4340 steel processed by hot forging. (The smaller inclusions are more detrimental at a given concentration because their number is larger.) Source: Ref 4

Special analytical methods are used to guarantee the cleanliness of a powder. Examples include wet analysis, emission or flame spectroscopy, atomic absorption, x-ray diffraction, and x-ray fluorescence. Some of these methods are described in the Section "Materials Characterizations" in this Handbook.

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Powder Production Processes

Metal powders are used in many other industries outside of powder metallurgy. The high capital cost of metal powder production and its sensitivity to economics of scale makes it mandatory for a powder producer to manufacture a wide range of powders of a given composition. Each powder manufacturing process has typical characteristics and limitations with respect to particle size, particle shape, microstructure, chemistry, and cost. Over the years, atomization has steadily gained in significance on account of its flexibility and cleanliness. This was at the expense of some ore derived, electrolytic and some hydrometallurgically-produced powders, due to technical, economic, and/or ecological factors.

Judicious selection of a powder is critical in P/M processing. Powder selected for optimal performance allows for smooth and efficient processing. Generally speaking, powders today are cleaner and have more uniform particle size distributions and particle shape and permit the production of superior and more consistent P/M products.

In the following sections the major mechanical, chemical, electrochemical and atomizing processes are briefly described.

Mechanical Processes. Mechanical-based powder production processes have low energy efficiency, and their commercial use today is therefore limited to brittle materials such as electrolytic iron chips, carbonized iron scarf, master alloys, and certain oxidation-sensitive and reactive materials. It is also used to produce metallic flake powders and in the manufacture of mechanically alloyed materials. The latter employs intense milling of multicomponent powders for the production of advanced dispersion strengthened materials. Milling is also employed for the manufacture of cemented carbides where intense mixing and good dispersion of the hardmetal and the binders are important.

In the so-called coldstream process, a relatively coarse powder is carried in a high-velocity, compressed gas onto a target. Adiabatic cooling of the compressed gas cools and embrittles the metal so that it disintegrates upon impact. This process is used to pulverize hard and abrasive materials, such as tungsten carbide, tool steels, and beryllium. The process is simple and produces a relatively oxide-free powder.

Crushing and milling are widely employed intermediate unit operations for converting sintered powder cakes into powder. Widely used mills include jaw crushers, ball mills, and hammer mills. For milling to fine powders, high energy mills (attritors and vibrating mills) and surface active milling additives can be used.

The particle shape of powders made by mechanical processing ranges from angular to irregular. Figure 8 shows a scanning electron micrograph of an electrolytic iron powder made by the milling of a brittle electrodeposited sheet. Figure 9 shows angular shaped copper particles made by hammer milling a sintercake of oxide-reduced copper. Figure 10 shows the effect of attritor milling on the particle shape of spherical (gas atomized) Ti-6Al-4V particles.

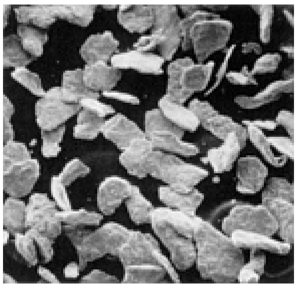

Fig. 8 Scanning electron micrograph of electrolytic iron powder. 75×. Source: Ref 5

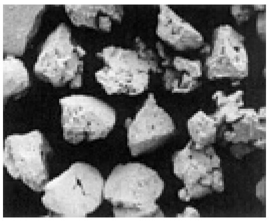

Fig. 9 Particles (+8 mesh) of copper powder hammer milled from oxide-reduced sinter cake. Source: Ref 5

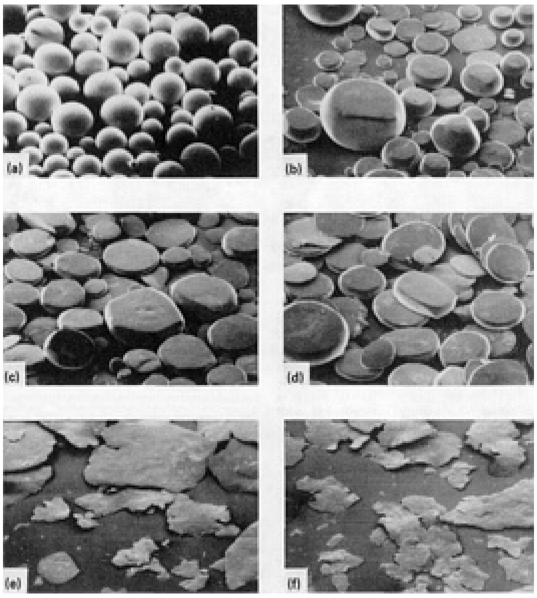

Fig. 10 Effect of milling time on particle shape change of spherical Ti-6Al-4V alloy particles. (a) As-received particle. (b) After 1 h. (c) After 2 h. (d) After 4 h. (e) After 8 h. (f) After 16 h. Source: Ref 5

Atomization. The mechanical disintegration of a melt, known as atomization, has become the most flexible and important method for producing metal powders for P/M use. There are several variants of this method (Fig. 11), but atomization with high pressure water or gas are the two most common. The use of centrifugal force to break up a liquid metal stream is known as centrifugal atomization; atomization into a vacuum as vacuum, or soluble-gas, atomization; and the use of ultrasonic energy to effect break up as ultrasonic atomization. Figure 12 shows a schematic of a typical water atomization process, including melting facility, atomizing chamber, and powder drying equipment.

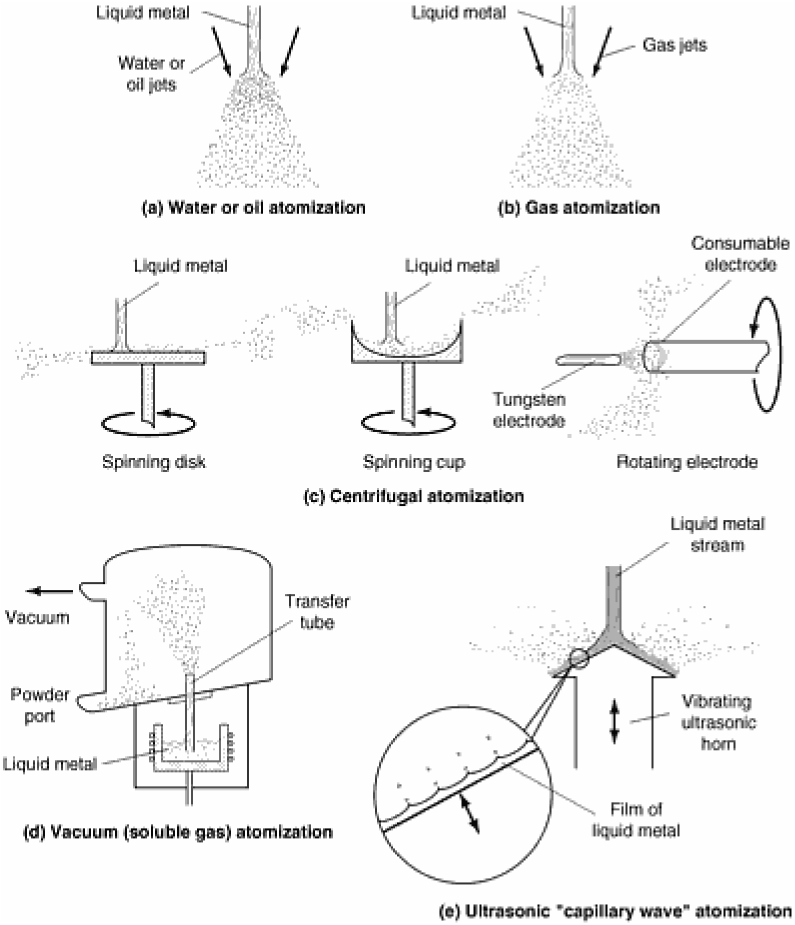
Liquid metal
Water or oil jets
(a) Water or oil atomization
Liquid metal
Gas jets
(b) Gas atomization
Liquid metal
Spinning disk
Liquid metal
Spinning cup
Consumable electrode
Tungsten electrode
Rotating electrode
(c) Centrifugal atomization
Vacuum
Transfer tube
Powder port
Liquid metal
(d) Vacuum (soluble gas) atomization
Liquid metal stream
Vibrating ultrasonic horn
Film of liquid metal
(e) Ultrasonic "capillary wave" atomization

Fig. 11 Schematic of atomization processes. Source: Ref 5

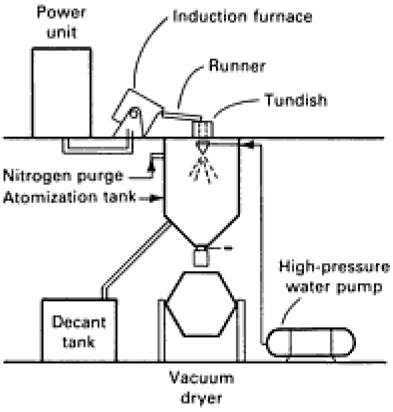
Power unit
Induction furnace
Runner
Tundish
Nitrogen purge
Atomization tank
High-pressure water pump
Decant tank
Vacuum dryer

Fig. 12 Water atomization setup. Source: Ref 5

Common to all atomization methods is the rapid quenching of the liquid particles at rates from 10^3 to 10^8 °C/s, depending on the particular atomizing process and particle size. The particle size of a water atomized powder is mainly controlled by the pressure of the water, which can be as low as 2.77 to 3.46 MPa (400 to 500 psi) units for a coarse or shotted powder, and as high as 20.7 MPa (3000 psi) for a very fine powder of a high melting point metal. The pressure range for gas atomized powders is smaller and narrower, typically from 0.69 to 2.77 MPa (100 to 400 psi).

The particle shape of gas atomized powders is usually spherical. Deviation from spherical can be attributed to oxidation during atomization in an oxidizing environment and/or to atomizing close to the melting point of the metal.

The particle shape of a water atomized powder is of great technical significance as it has a marked effect upon apparent density, green strength, and compressibility. The most important parameters that control the particle shape of a water atomized powder include the atomizing temperature (i.e., the temperature of the liquid metal), the cooling rate during atomization, the design of the atomizing nozzle system, and the degree of oxidation occurring during atomization. So-called dual atomization employs superimposed jets of gas and water and extends the control of both particle size and particle shape.

Some P/M processes require the use of powders of relatively narrow particle size distributions. With a good gas or water atomization system, it is possible to produce powders where two-thirds of the mass of the particle size distribution have a particle size range with a size ratio of less than four. Powders made by centrifugal atomization (spinning disk, rotating electrode) can have even narrower particle size distributions because of the uniform centrifugal force acting upon a thin and uniform sheet of liquid metal, plus the near absence of particle collisions (Fig. 13).

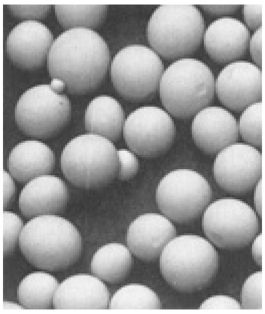

Fig. 13 Scanning electron micrograph of plasma rotating electrode processed René 95 powder particles. Approximately 70×. Source: Ref 5

The oxides formed during water atomization are distributed mainly on the surfaces of the individual particles. As shown in Fig. 14, these oxides, in alloys, consist predominantly of elements that are of small atomic size, which diffuse and oxidize rapidly. In superalloys, these oxides are difficult to remove; it is for this reason that superalloy powders are produced exclusively by inert gas atomization methods, which limits the oxygen contents to that of the liquid melt prior to atomization. Water atomized tool steels and stainless steels are examples where surface oxides (silicon oxides in stainless steels) are reduced during sintering at high temperature in a low dew point furnace atmosphere (or by carbon in vacuum sintered tool steels), which accounts for their widespread use. For iron and copper powders the oxides formed during atomization are reduced during powder annealing or during sintering.

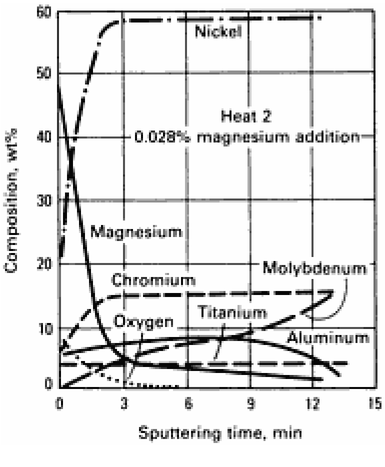

Fig. 14 Auger composition-depth profile of argon-atomized nickel-base superalloy powder. Source: Ref 5

In one commercial process for the production of iron powder, a high carbon iron melt is water atomized in the presence of air. This results in the partial oxidation of iron. In a subsequent heat treatment, carbon reacts with oxygen to form a protective atmosphere of CO and a low carbon content compressible iron powder.

The rapid quench rates attainable with atomization are related to the so-called dendrite arm spacing of the microstructures of the powders, as shown for aluminum alloys in Fig. 15. Glassy or amorphous particles can be found in the fine fractions because of the higher cooling rates of fine powders. Rapid quenching reduces segregation, refines the microstructure, and extends the solubility of a metal, with benefits in hot formability, fatigue and impact strength, and electrical and magnetic properties. In alloys that form precipitates on cooling, such precipitates generally are uniform in size and small compared to those in ingots of the same composition. Figure 16 shows such a comparison of microstructures for T15 high-speed tool steel. The benefits of these differences, improved formability and toughness, have led to the increasing use of P/M tool steels. Low alloy steels and superalloys are other examples where rapid cooling benefits have been exploited for two or three decades. New alloys continue to be developed, often in combination with consolidation to full density.

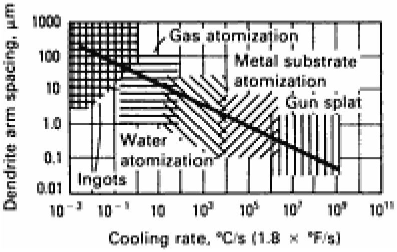

Fig. 15 Dendrite arm spacing versus cooling rate for aluminum alloys. Source: Ref 5

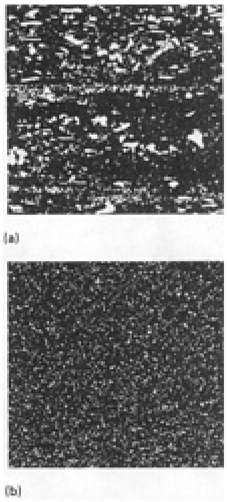

Fig. 16 Microstructures of T15 tool steel. (a) Wrought. (b) Powder metallurgy processed. Source: Ref 5

Chemical Processes. After atomization, next in importance are chemical processes of powder production for P/M uses. These include reduction of oxides, precipitation from solution or from a gas, thermal decomposition, chemical embrittlement, hydride decomposition, and thermit reactions. The most widely used processes within this category include oxide reduction, precipitation from solution, and thermal decomposition.

Oxide Reduction. This method of powder manufacture is widely used for the production of iron, copper, tungsten, and molybdenum powders from their oxides. Such powders are also known as sponge powders because of the presence of pores within the individual particles (Fig. 17). Most commercial processes of oxide reduction employ stationary-type reduction in belt furnaces. The reducing gas composition required for successful reduction depends on the particular metal oxide and the reduction temperature. The reduced oxide is actually a porous cake that must be ground to powder; sometimes the ground powder is annealed to further remove oxygen and/or carbon and to render it soft. The choice of reducing media (hydrogen, carbon monoxide, or carbon), raw material quality and size, and reduction conditions (temperature, bed depth, etc.) permits the manufacture of powders with a broad range of characteristics. Reduction temperature is perhaps the most critical process variable. Low reduction temperatures result in powders possessing fine pores, large specific surface areas, low apparent densities, and high green strength. High reduction temperatures (>0.6 *T*) produce large intraparticle pores and small specific surface area powders with good compressibility.

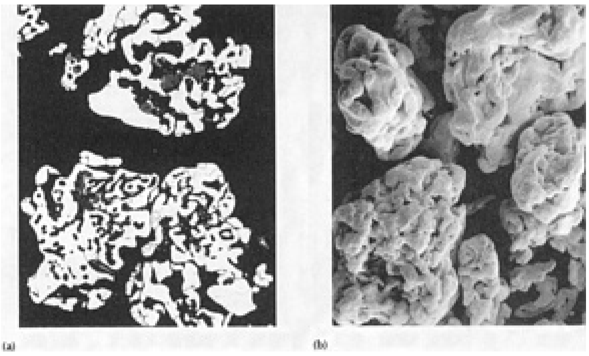

Fig. 17 Sponge iron particles. (a) Cross section. (b) Scanning electron micrograph. Both 180×. Source: Ref 5

The most important commercial process for oxide-reduced iron powder, the Höganäs process, is based on the direct reduction of a high-purity magnetite ore. Beneficiation and magnetic separation reduce the level of silicon dioxide to approximately 0.2%. Because of this, the powder is mainly used in low and medium density P/M applications where the deleterious effects of oxide inclusions are overshadowed by the effect of pores.

Oxide reduced powders of high purity made from high purity oxides include iron, copper, tungsten, and molybdenum. Oxide-reduced powders, because of their superior green strength characteristics, are often preferred in applications where green strength is important (i.e., friction parts) and where compressibility is of lesser importance. Sponge powders, as a result of their porous structure and larger surface area, shrink more than atomized powders during sintering, and they are sometimes added to atomized powders to modify and/or adjust the shrinkage characteristics of a powder.

Precipitation from Solution. Production of metal powders by hydrometallurgical processing is based on leaching an ore or ore concentrate, followed by precipitating the metal from the leach solution by electrolysis, cementation, or chemical reduction. In the Sherritt-Gordon process, copper, nickel, and cobalt are separated and precipitated from salt solutions by reduction with hydrogen. Hydrogen pressure, solution pH, and solution temperature must be controlled for successful reduction and differ for different metals. Through the use of additives and control of nucleation, powders with a wide range of particle sizes, particle density, and particle shape may be produced.

Through co-precipitation or successive precipitation of different metals, alloyed and composite powders can be produced.

Thermal Decomposition. Of the group of thermally decomposed powders, those produced by thermal decomposition of carbonyls are the most important. Both iron and nickel are produced by decomposition of their carbonyls.

Carbonyls are obtained by passing carbon monoxide over sponge metal at specific temperatures and pressures. Powder is produced by boiling the carbonyls in heated vessels at atmospheric pressure. The powder can be milled and annealed in hydrogen. The chemical purity of the powder can be high (over 99.5%) with the principal impurities being carbon, nitrogen, and oxygen. Particle size can be controlled very closely. Iron carbonyl powder is usually spherical in shape and less than 10 μm in diameter. Nickel carbonyl powder is usually available as a fine spiky, a fine filamentary, and fine or coarse, high density powder.

Electrochemical Processes. Copper, iron, manganese, and silver are the main metals produced commercially by electrodeposition. Depending on the electrochemical polarization characteristics of a metal, it can be deposited as a loosely adhering, powdery deposit on the cathode, or as a smooth, dense, and brittle deposit, which subsequently is milled into powder. In metals where the deposition potential varies little with current density, such as copper, silver, zinc, and cadmium, powdery deposits form. Iron, nickel, manganese, and cobalt require a large change in cathode potential for a small change in current density. These deposits are dense. Their brittleness can be controlled to some extent by proper adjustment of the electrolytic cell conditions.

The singularly outstanding quality of electrolytic powders is high purity. Before the advent of atomized powders, electrolytic iron and copper powders were widely used in the manufacture of electrical and magnetic P/M parts and also for high density parts because the high purity of the metals provided superior electrical, magnetic, or high compressibility characteristics. The relatively high purity of atomized powders has bridged this gap to a considerable extent. In addition, the high processing cost of electrolytic powders, in part related to environmental factors, has widened the cost differential between electrolytic and other types of metal powders.

Particle shape and size of loosely deposited electrolytic powders depends on the electrolytic cell conditions and can be additionally controlled through the use of addition agents to the electrolyte. Subsequent annealing can be used to stabilize the powders against oxidation and to broaden the range of powder characteristics. Commercial electrolytic copper powders have particle shapes from dendritic to equiaxed irregular and apparent densities from less than 1 g/cm^3 to over 3 g/cm^3. The particle shape of electrolytic iron powder, as a result of milling, is irregular and flaky, with fairly rough surfaces. Table 1 compares chemical and physical properties of typical compacting-grade iron powders made by electrolysis, oxide reduction, and atomization.

Table 1 Chemical and physical properties of compacting-grade iron powder

Constituent or property	Electrolytic	Reduced	Atomized
Chemical analysis, %			
Total iron	99.61	98.80	99.15
Insolubles	0.02	0.10	0.17
Carbon	0.02	0.04	0.015
Hydrogen loss	0.29	0.30	0.16
Manganese	0.002	. . .	0.20
Sulfur	0.01	0.007	0.015
Phosphorus	0.002	0.010	0.01
Physical properties			
Apparent density, g/cm^3	2.31	2.40	3.00
Flow rate, s/50 g	38.2	30.0	24.5
Sieve analysis, %			
+100	0.5	0.1	2.0
-100 + 150	13.1	7.0	17.0
-150 + 200	22.6	22.0	28.0
-200 + 325	29.4	17.0	22.0
-325	34.4	27.7	22.0
Compacting properties(a)			
Green density, g/cm^3	6.72	6.51	6.72
Green strength, MPa (psi)	19.7 (2800)	19.0 (2700)	8.4 (1200)

Source: Ref 5

(a) At 414 MPa (30 tsi) with 1% zinc stearate.

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Powder Treatments

Most powders receive one or more treatments prior to compaction. These treatments are tailored to the use of a powder and may include particle size distribution adjustment through screening and/or air classifying, annealing for the purpose of improving compacting properties, lubricant addition for compacting grade powders, mixing of different powders for premixes, and blending of powders and powder mixes to homogenize their various components. These treatments are usually performed by the powder producer. The quality of these treatments can greatly affect the uniformity and consistency of sintered part properties. With increasing emphasis on zero-defect manufacture, the treatments have received more attention in recent years.

Classifying/Screening. Many powder production processes yield relatively broad particle size distributions, and because of the many manufacturing variables, the distributions and average particle sizes may exhibit marked lot-to-lot variations, which contribute to the variation of important powder and sintered part properties. Classifying and screening are used to render the particle size distributions of powders more uniform with well-defined, upper particle size limits. Powder producers often manufacture series of powders that differ only in particle size distribution. Such powders exhibit "graded" differences in dimensional change during sintering. For filter manufacture, classifying and screening is used to generate narrowly sized powder fractions for controlled pore size in filters and flow restrictors.

Powder Mixtures and Segregation of Powders. Most P/M metal powders are multicomponent systems and, therefore, are subject to segregation. Segregation is even possible in a one-component metal powder if, for instance, coarse and fine powder particles "demix" as a result of vibration. The opportunity for powder segregation exists in processes such as shipping and filling of hoppers and compaction dies, where individual components, on account of differences in particle size, shape, density, surface roughness, and other properties, exhibit different flow rates.

The most widely used P/M compacting grade powders are mixtures of iron with graphite, copper, nickel, and/or molybdenum. The preferred use of powder mixtures rather than of prealloyed powders is related to several factors. The most important factor is that elemental powder mixtures generally possess significantly higher compressibilities than their prealloyed counterparts. Secondly, powder mixtures are usually less expensive than prealloyed powders. And thirdly, powder mixtures more often can be formulated to provide transient liquid phases during sintering, which can reduce sintering times and improve mechanical properties.

In most powder mixtures, the base powder typically comprises 90% or more of the powder mixture. As the other components are present in only small amounts, and their alloying effects are powerful, it is very important that they are uniformly distributed and that the homogeneity of the powder is preserved during shipping of the powders and during handling at the parts producer's site until compaction is completed. Without such precautions, the properties of the sintered parts are not optimal and the standard deviation, that is, the scatter of the properties, can be quite large.

Stabilization of Multicomponent Powder Mixtures. Because of the wide use of powder mixtures and their sensitivity toward demixing, much work has been done toward the stabilization of powder mixtures.

Stabilizers. A powder mixture is optimally mixed if its components approach a random (statistical) distribution that is free of agglomeration (Fig. 18). The quality of mixing can be measured by the number of particle contacts (in green compacts) between identical or different powder components as illustrated in Fig. 19 for iron-copper mixtures, or by the chemical analysis of appropriate samples taken from the powder mixture.

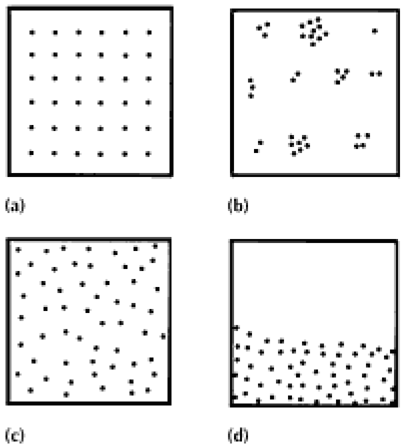

Fig. 18 Schematic representation of particle patterns in a powder mixture. (a) Ordered. (b) Agglomerated. (c)

Statistical (random) distribution. (d) Demixed or segregated. Source: Ref 6

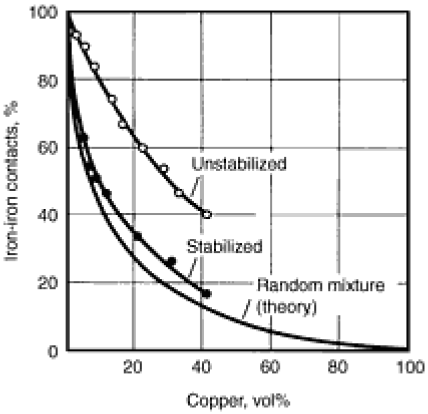

Fig. 19 Effect of stabilizer on iron-iron contact formation in binary iron-copper system. Source: Ref 6

Blenders and mixers that rely mainly on gravity (tumblers) are suitable for powders that mix readily. More intense mixing is accomplished with low-shear, agitated-type blenders that use ribbons, slow-speed paddles, screw-type augers, or other means of motion. Figure 20 illustrates how spherical powders mix quite readily, but also are subject to demixing or overblending. Consequently, mixing should be stopped once a near-random distribution has been achieved. The variability coefficient in Fig. 20 represents the standard deviation of the measured degree of mixing divided by the average value of the measured property. The quality of the mixture improves with decreasing variability coefficient.

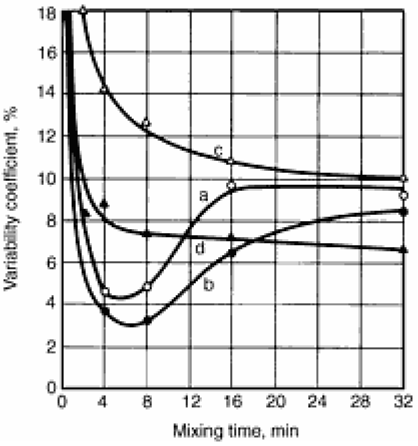

Fig. 20 Effect of particle size and shape of components of 90%Fe-10%Cu mixtures on degree of blending. Quality of blending improves as variability coefficient decreases. Particle size and shape for components: (a) Cu, 200 to 300 μm; Fe, <63 μm of spherical particle shape. (b) Cu, 200 to 315 μm; Fe, 100 to 200 μm of spherical particle shape. (c) Cu, 200 to 315 μm; Fe, <63 μm of irregular particle shape. (d) Cu, 200 to 315 μm; Fe, 100 to 200 μm of irregular particle shape. Source: Ref 6

Demixing is often caused by the accumulation of electric charges, which often can be dissipated by the addition of a small amount of water. Surfactants and stabilizers are sometimes used to improve the flow of materials. They consist of wetting liquids and oils that have no negative effects on the sintering process. Figure 21 shows the beneficial effect of oleic acid (dissolved in benzene) for 90%Fe-10%Al mixtures. In this example, the best mixture results from the addition of the optimized amount of a stabilizer after eight minutes of mixing, when the mixture has approached a random distribution (curved).

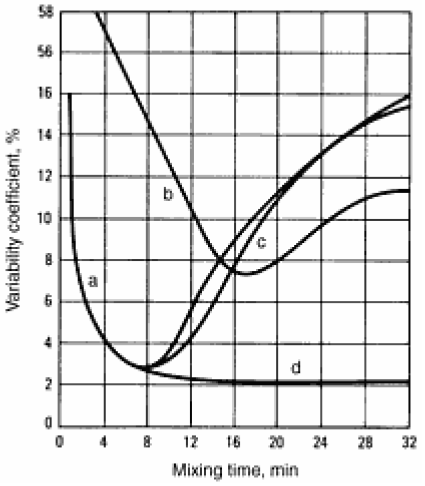

Fig. 21 Effect of stabilizer on degree of blending of 90%Fe-10%Al mixtures. Particle size for both components: 100 to 200 μm. Stabilizer: benzeneloleic acid. (a) Without stabilizer. (b) With 1.0% stabilizer. (c) 1.0% stabilizer added after 8 min of blending. (d) 3% stabilizer added after 8 min of blending. Source: Ref 6

Diffusion-Bonded Powders. In a diffusion-bonded powder, a powder mixture is heated in a reducing atmosphere to yield a sintered powder cake, which, after grinding, produces a powder that consists of agglomerates of the components of the powder. The process is controlled so that the degree of alloying between the different components is only small. This retains much of the desirable high compressibility characteristics of the original elemental powder mixture and minimizes or eliminates the demixing tendency of such a powder. As a bonus, green strength is usually increased.

Binder-Treated Powders. In recent years powder producers have developed proprietary binders, which are used in small amounts to bond fine graphite onto the coarser iron particles. Such powders reduce the dusting of a powder and improve the uniformity of several important engineering properties of the sintered parts because of the more uniform concentration of carbon in the final parts.

Prealloyed Powders. In spite of the widespread use of powder mixtures, the use of prealloyed powders in the structural parts industry has been increasing. In the low alloy steel segment, nickel, molybdenum, and manganese are used as alloying elements to provide greater hardenability than is possible with admixed copper or nickel. Admixed nickel requires economically prohibitive sintering times (even at high sintering temperatures) for complete alloying. Higher alloyed powders, such as stainless steels, tool steels, and superalloys, are all prealloyed powders. The requirement of complete alloying in these alloy classes makes the elemental powder approach impractical. The problem of low compressibility, that is, low green density and/or low green strength, is solved by high temperature and liquid phase sintering and through the use of special consolidation methods such as hot isostatic pressing and extrusion.

Annealing. Although the term annealing refers to a heat treatment that renders a metal soft by the removal of strain, in P/M the term is used more broadly and includes the softening of a powder by the removal of interstitials, particularly carbon, nitrogen, and oxygen. Powders that have been work hardened through milling, powders that contain residual amounts of carbon, oxygen, or nitrogen, and powders that contain objectionable surface oxide films are most often subjected to this type of annealing. Examples include sponge and atomized iron powders, carbonyl and electrolytic iron powders, tool steel powders, and ferritic stainless steel powders. In most cases, annealing is performed in a reducing atmosphere that not only protects the powder against oxidation, but also removes surface and interior oxides. Annealing improves the compressibility and green strength of a powder due to the softening of the metal. Frequently, annealing also produces slightly agglomerated powders with lower apparent densities and further increases in green strength.

Lubrication. Compacting grade metal powders are lubricated to facilitate part ejection from the die and to minimize die wear. Lubricants can strongly affect compacting and sintering properties of a powder. For this reason, powder producers try to optimize amount, composition, and structure of a lubricant to not only reduce friction during powder compaction, but also to protect the powder against oxidation, to obtain consistent apparent density and powder flowability, proper dimensional change during sintering, and maximum and consistent mechanical properties of the sintered parts. Widely used lubricants are zinc stearate, stearic acid, lithium stearate, and synthetic waxes. Typical lubricant concentrations vary between 0.5 and 1.5 wt%. Although a lubricant largely evaporates and/or decomposes in the preheating zone of a sintering furnace, interactions and reactions with the metal powder can have critical consequences. Potential problems range from lubricant segregation, burnout, and blistering to carbonization and lubricant residue interference. Lubricant performance also depends on part density and metal powder composition and particle size.

Lithium stearate is widely used in stainless steel powders because of its beneficial effect on compressibility. Lithium stearate and zinc stearate mixtures are used in brass and nickel silver powders to produce stainfree parts. Synthetic waxes, with their low moisture and ash contents, are widely used for high density parts, where ash residues are objectionable. Multicomponent lubricants permit the powder producer to adjust or influence the packing, pressing, and sintering characteristics of a powder. Figures 22, 23, 24, and 25 illustrate various effects of lubricants.

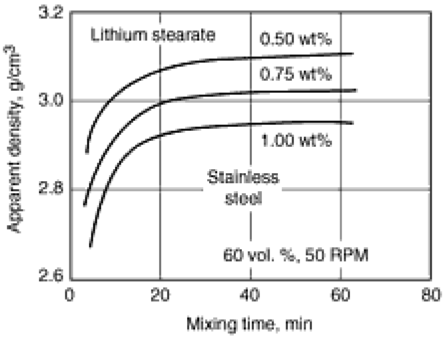

Fig. 22 The apparent density of a lubricated water atomized stainless steel powder as function of mixing time. The plot shows the apparent density versus the amount of lubricant. The conditions were 60 vol% fill in a double cone mixer rotating at 50 RPM, lithium stearate ranging from 0.5 to 1.0 wt%. Source: Ref 4

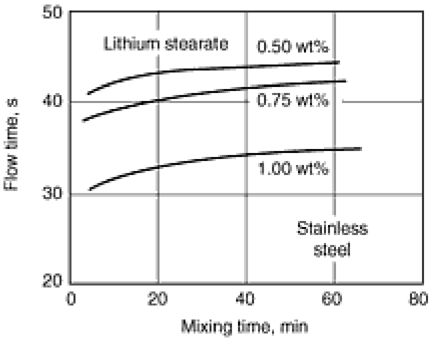

Fig. 23 The effect of powder lubrication on the flow time as measured by the Hall flowmeter. The experimental conditions correspond to those reported in Fig. 22. Source: Ref 4

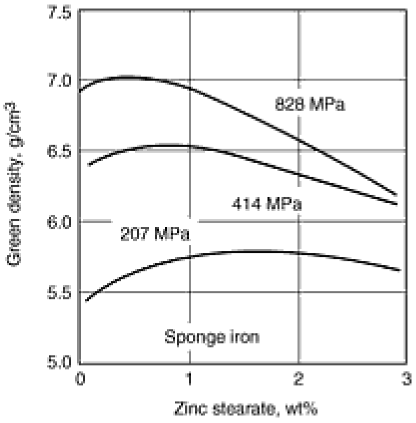

Fig. 24 The effect of powder lubrication on the green properties of pressed sponge iron. The green density is shown as a function of the amount of zinc stearate for three compaction pressures. Source: Ref 4

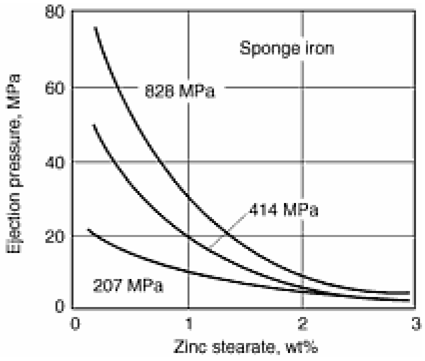

Fig. 25 The effect of the amount of zinc stearate on the ejection force (the force necessary to remove the compact from the die after pressing) of a compact. Source: Ref 4

The use of die wall rather than admixed powder lubrication is still in the development stage.

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Powder Consolidation

The techniques for forming and shaping metal powders are diverse and continue to evolve. This is directly related to the wide range of densities used in P/M products: from very low-density metallic forms to low- and medium-density filters and self-lubricating bearings, and high- and full-density structural parts. In the most widely employed technique, powders are compacted into green parts at room temperature and then sintered. There are, however, P/M techniques that use no compacting step and others that combine forming and sintering in one operation. Regardless of the density of the final part, the general requirement of a sintered part is that there is good metallurgical bonding between powder particles and that the presence of any defects (that is, pores, inclusions, original particle boundaries, etc.) is controlled in a manner that guarantees specified performance properties. The density of a part is, of course, a very fundamental property, and apart from some unique products such as filters and porous self-lubricating bearings where porosity itself is of functional importance, the highest economically feasible density is usually sought in order to obtain the highest possible strength properties. Broadly speaking, increasing density is synonymous with increasing cost of a P/M part; however, the relationship is not strictly linear in that it shows abrupt changes when the consolidation technique changes (Table 2).

Table 2 Approximate costs of steel P/M parts produced by various methods

Condition	Density range, g/cm^3	1997 selling price[(a)], \$/lb
Pressed and sintered	6.0-7.1	2.45-2.70
Pressed, sintered, sized	6.0-7.1	2.90-3.20
Copper infiltrated	7.3-7.5	3.50-3.55
Warm formed	7.2-7.4	3.10-3.30
Double pressed and sintered	7.2-7.4	4.00-4.10
Metal injection molded	7.5-7.6	45.0-70.0
Hot forged	7.8	5.00-5.50

Double press and sinter and hot isostatic pressing	7.87	6.00-7.00

(a) These numbers are only averages; smaller parts are more expensive and larger parts less expensive per pound.

Figure 26 shows schematically the dependence of sintered density and of several mechanical properties on sintering temperature. Conventional pressing and sintering with maximum densities around 90 to 92%, and up to approximately 95% for double pressed parts, can achieve impressive relative strength values. However, ductility, and more so dynamic strength properties such as impact and fatigue strength, are relatively low because these properties, unlike ultimate tensile strength, depend more upon the morphology of the pores (both size and shape) and approach their maximum values at full density in an exponential fashion. As the so-called high and full density techniques are more expensive than conventional pressing and sintering, it is therefore imperative in the design of a new part first to identify the requirements of the intended application. To select the least expensive P/M technique for the manufacture of a part requires a broad and detailed understanding of the various P/M processes and is best done in consultation with a P/M parts manufacturer. There are many examples where wrought parts have been replaced by porous P/M parts of much lower ductility that yielded satisfactory performance. Size, shape, surface finish, mechanical and physical properties, dimensional tolerance requirements, as well as quantity and cost restrictions enter into the decision-making process for selecting the proper consolidation method. Tables 3 and 4 compare several of these characteristics for various P/M processes.

Table 3 Comparison of powder processing methods

Characteristic	Conventional	Metal injection molding	Hot isostatic pressing	Powder forging
Size	Good	Fair	Excellent	Good
Shape complexity	Good	Excellent	Very good	Good
Density	Fair	Very good	Excellent	Excellent
Dimensional tolerance	Excellent	Good	Poor	Very good
Production rate	Excellent	Good	Poor	Excellent
Cost	Excellent	Good	Poor	Very good

Source: Ref 7

Table 4 Application of powder processing methods

	Conventional die compaction	Metal injection molding	Hot isostatic pressing	Powder forging
Material	Steel, stainless steel, brass, copper	Steel, stainless steel	Superalloys, titanium, stainless steel, tool steel	Steel
Production quantity	>5000	>5000	1-1000	>10,000
Size, lb	<5	$<\frac{1}{4}$	5-5000	<5
Dimensional tolerance	±0.001 in./in.	±0.003 in./in.	±0.020 in./in.	±0.0015 in./in.
Mechanical properties	∼80-90% wrought	∼90-95% wrought	Greater than wrought	Equal to wrought
Price per pound	$0.50-5.00	$1-10	>$100	$1-5

Source: Ref 7

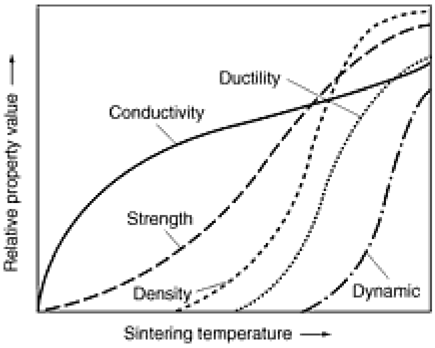


Fig. 26 Variation of sintered density and compact properties with the degree of sintering as represented by the sintering temperature. Source: Ref 4

Conventional Pressing and Sintering

Conventional compaction and sintering is the most widely employed technique for producing P/M parts. Figure 27 shows the processing steps.

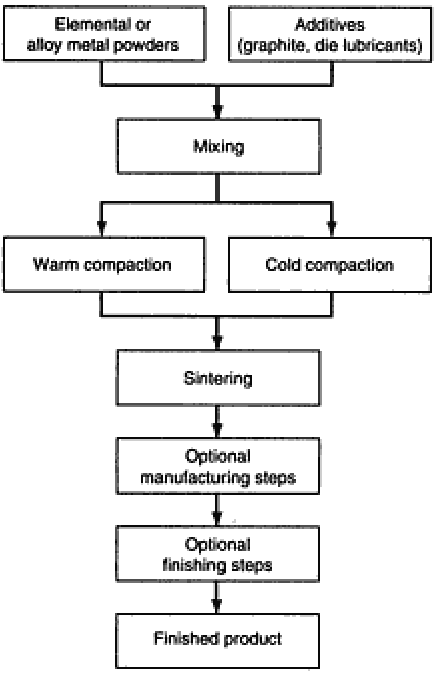

Elemental or alloy metal powders
Additives (graphite, die lubricants)
Mixing
Warm compaction
Cold compaction
Sintering
Optional manufacturing steps
Optional finishing steps
Finished product

Fig. 27 General steps in the P/M process. Source: Ref 7

Compaction of Powders. As a metal powder deforms during compaction, its hardness increases (work hardening), and its rate of densification decreases with increasing compaction pressure, as shown in Fig. 28. Cold welding and interlocking of particles provides compact green strength. Densities above 90% of theoretical are difficult to attain for many metal powders because of the increasing work hardening. High compressibility powders are, therefore, preferred in systems that require high compacting pressures, such as iron, stainless steel, and tool steel powders. Typical and maximum compaction pressures employed in the industry for these powders are in the range of 550 to 827 MPa (40 to 60 tsi).

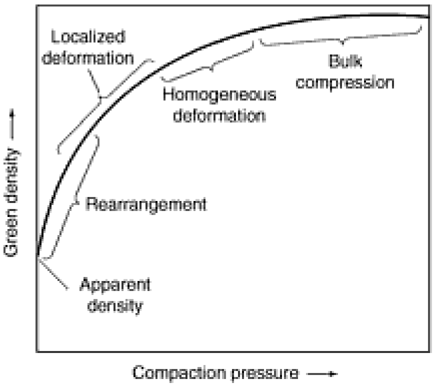


Fig. 28 Key steps during compaction and effect of compacting pressure on green density. Source: Ref 4

Density increases up to approximately 95% of theoretical can be obtained by repressing after sintering. The attainment of a high density by sintering at a high temperature and/or for a long period of time usually requires repressing of the sintered part in order to restore acceptable dimensional tolerances.

In the most common compaction technique, double action compaction pressure is applied along one vertical axis, from both top and bottom, as shown in Fig. 29. The punches provide compression forces while the die provides lateral support to the powders. To press parts of identical weight, it is important that the apparent density of a powder and its flow and packing properties are constant.

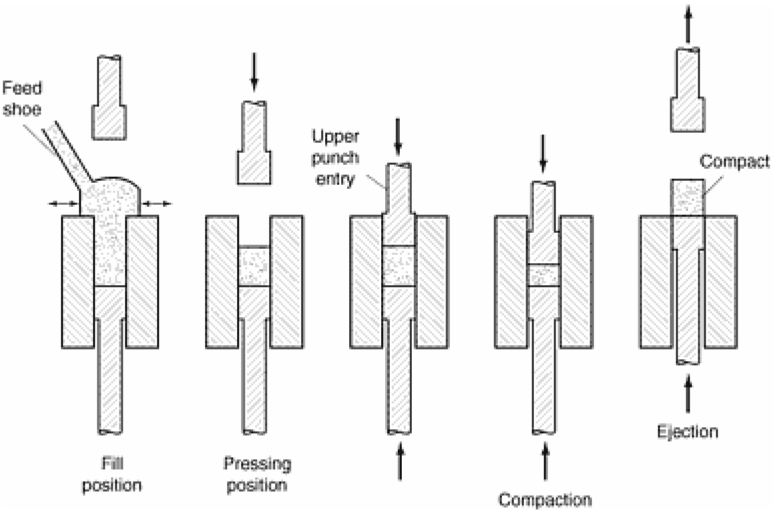


Fig. 29 Tool motions during a powder compaction cycle, showing the sequence of powder fill, pressing, and ejection. Source: Ref 4

In spite of the use of lubricants, residual friction between die walls and powder and within the powder itself and the nonisotropic application of pressure result in nonuniform density throughout the part. Figure 30 shows the density distribution (lines of constant density in g/cm^3) of a cylinder pressed from nickel powder from only one direction, at a pressure of 690 MPa (100 ksi). The low density near the bottom of the compact explains the widespread use of double action compaction. The density differences (and the implicit variations in stresses and contact geometries) are the main reason why compacts, upon sintering, do not shrink uniformly and why sintering of such compacts is, therefore, performed under conditions that result in only small dimensional changes. With substantial shrinkage, dimensional tolerances deteriorate rapidly and require sizing.

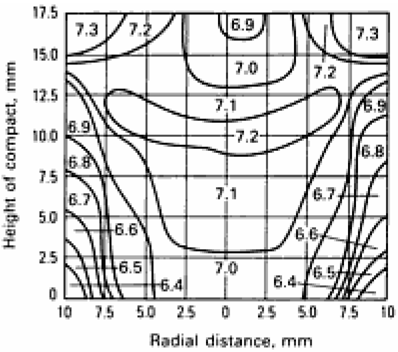


Fig. 30 Density distribution in a cylindrical nickel powder compact. Source: Ref 5

Design Limitations. The vertical compaction motion and the requirement that a part be automatically ejected from the die impose size and shape limitations. Additional limitations arise from the necessity that die components resist fracture and that the flow of powder into the die must be possible for uniform density. Generally, the wall thickness of a part is not less than 1.5 mm (0.060 in.). A maximum length-to-wall thickness ratio of 8 to 1 ensures reasonable density uniformity. Simple steps or level changes not exceeding 15% of the overall part height can be formed by face contours in the punches. This requires a draft of at least 5° for proper ejection.

Spherical parts require a flat area around a major diameter to allow the punch to terminate in a flat section (Fig. 31). Parts that must fit into ball sockets are repressed after sintering to remove the flats. Through holes in the pressing direction are produced with core rods extending through the punches.

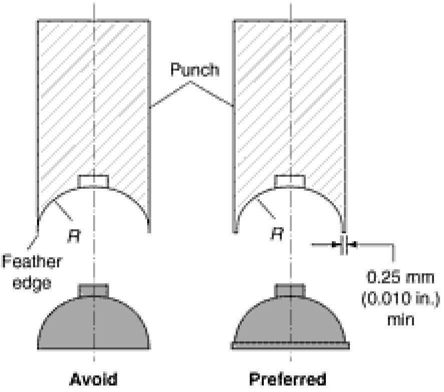


Fig. 31 Proper design of spherical shapes in P/M parts. Source: Ref 7

Chamfers are preferred rather than radii on part edges to prevent burrs. Figures 32 and 33 show examples of unacceptable, acceptable, and preferred design features.

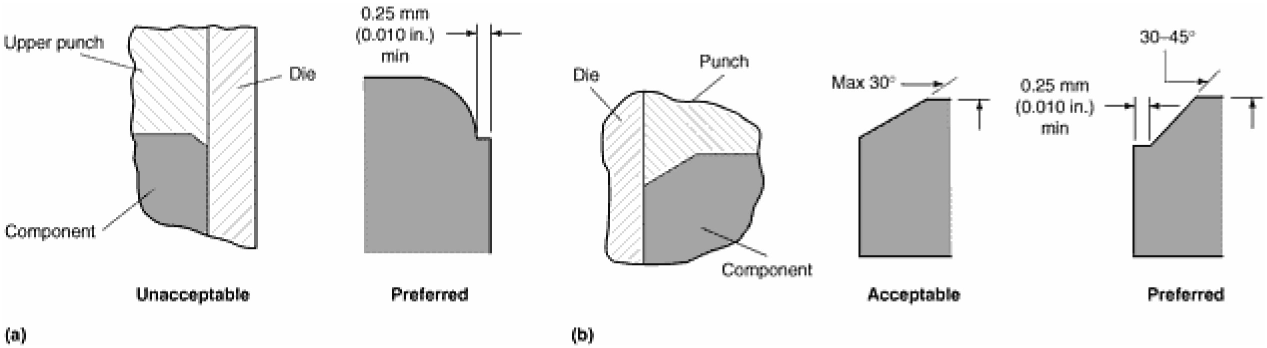
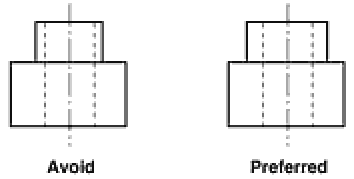
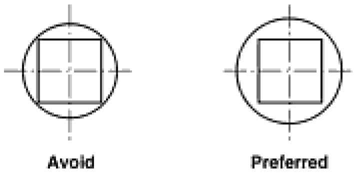

Upper punch
Die
Component
0.25 mm
(0.010 in.)
min
Unacceptable
Preferred
(a)
Die
Punch
Component
Max 30°
0.25 mm
(0.010 in.)
min
30–45°
Acceptable
Preferred
(b)

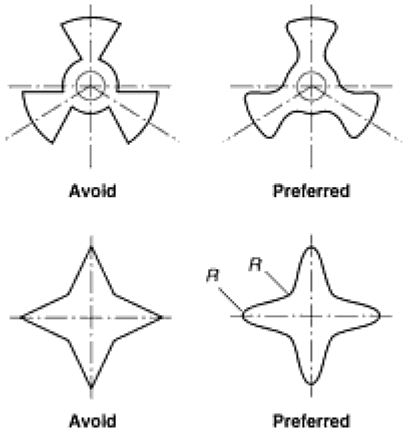
Fig. 32 Chamfer (a) and edge radii (b) design features. Source: Ref 7


Avoid
Preferred

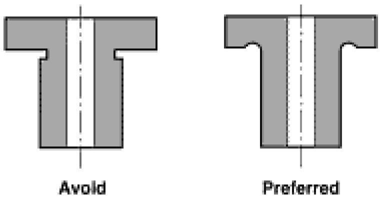
Avoid abrupt changes in mass that can induce distortion during sintering and heat treatment


Avoid
Preferred

Avoid localized thin walls


Avoid
Preferred
R
R
Avoid
Preferred

Use radii to relieve sharp interior corners and feather edges


Avoid
Preferred

Avoid grooves that require secondary machining (the preferred groove can be pressed)

Fig. 33 Examples of undesirable design features and preferred alternatives for P/M parts. Source: Ref 7

Reference 8 provides more details on designing for P/M. The limitations of shape complexity in the conventional press and sinter technique can be overcome in part by so-called multiple part assembly through sinter bonding, brazing, or welding.

With a large press (∼1000 tons capacity) and a high compressibility powder, commercially produced parts can weigh around 2 kg (4.4 lb), with a compaction area of approximately 160 cm^2 (62.99 in^2), and a part thickness of approximately 75 mm (2.96 in.) although larger and heavier parts have been produced on conventional equipment.

Springback of a part, that is, expansion after ejection from the die as a result of the release of elastic stresses, must be included in die design. Springback is usually less than 0.3% of the die dimension.

Dies are typically made from tool steel or cemented carbide. The latter are used in high volume production.

Powder metallurgy parts are classified by their complexity in terms of the number of their so-called levels or thicknesses and pressing directions (single or double action). Multiple level parts are the most difficult to press as each level requires separate punches for independent motion in order to minimize density differences between the various levels, (Fig. 34). Figure 35 illustrates the capabilities of the P/M press and sinter process in terms of the four compaction classes.

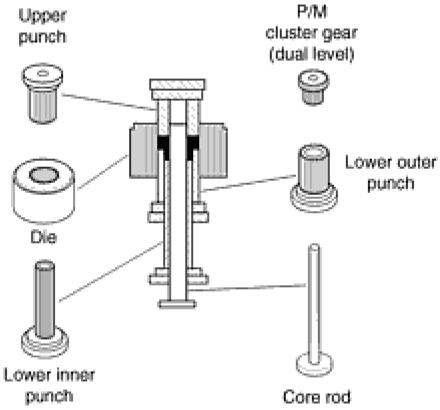


Fig. 34 The multiple tool components needed to compact a two-level gear. Source: Ref 4

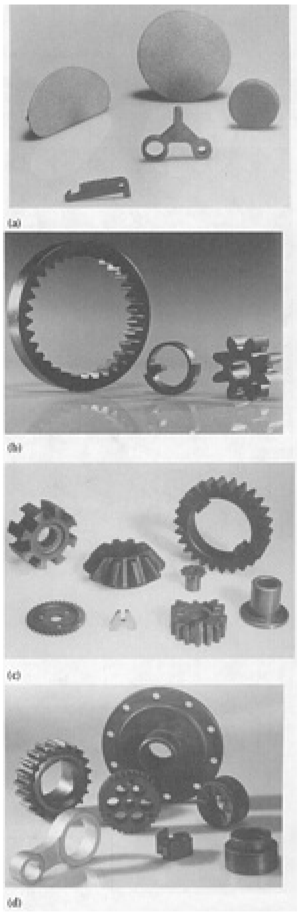


Fig. 35 Collection of P/M components demonstrating the variety of possible shapes and the four compaction classes. (a) Class 1. (b) Class 2. (c) Class 3. (d) Class 4. Courtesy of Randall M. German, The Pennsylvania State University

P/M presses can be of the hydraulic, mechanical, pneumatic, rotary, or isostatic type. Hydraulic presses have press capacities from less than 100 tons (896 kN to over 2000 tons, or 17,920 kN). Ejection of a pressed part from the die may be by the lower punches or by the so-called withdrawal type tooling. Rotary presses are cam-operated, high-speed presses. They are used for compacting small parts and can produce small bearings at rates of several 100 per min. Small mechanical presses (up to approximately 20 tons, or 179 kN) can produce parts up to approximately 100 per min, larger presses (>100 tons, or 896 kN) can produce up to approximately 25 parts per min.

Hydraulic presses are controlled by compacting load, and mechanical presses are controlled by compact dimensions. If, therefore, the apparent density of a powder fluctuates toward a higher value, a hydraulically pressed part is bound to be of slightly larger height, while a mechanically pressed part will have a slightly higher density. Herein lies the importance of uniform apparent density of a powder lot to assure uniform parts for the entire powder lot. Hydraulic presses are slower than mechanical presses, but they allow more uniform densities and more independent controls.

Complex shapes involving undercuts or large length-to-diameter ratios can be formed by cold isostatic pressing. Using this process, a flexible mold is filled with powder and pressurized isostatically (at ambient temperature), using a fluid such as oil or water. Compacting pressures ranging from 210 to 410 MPa (30 to 60 ksi) are most commonly employed, although pressures as high as 1400 MPa (200 ksi) have been used.

Sintering. Sintering is the process through which the particle contacts achieved during compaction grow (Fig. 36) and the physical and mechanical properties of a part are developed. Frequently, it is accompanied by shrinkage of the part. Sintering can also involve alloying and homogenization of mixed powder parts, often accompanied by growth.

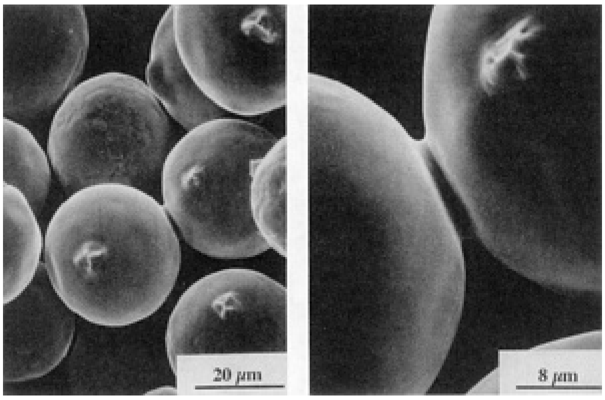


Fig. 36 Scanning electron micrographs of the neck formation due to sintering. The spheres (33 μm diam) were sintered at 1030 °C for 30 min in vacuum. Courtesy of Randall M. German, The Pennsylvania State University

Sintering is performed at temperatures around $\frac{2}{3}$ of the absolute melting point of the material, typically for 20 to 60 min and under a protective atmosphere. Widely used furnace atmospheres include endothermic gas, exothermic gas, dissociated ammonia, hydrogen, hydrogen-nitrogen mixtures, and vacuum. The main function of the atmosphere is to protect a part from oxidation or nitridation, as might occur when heating in air. Frequently, however, critical aspects of a sintering atmosphere also include reducing and carbonizing power and capability for efficient removal of the lubricant. Some sintering furnaces contain so-called rapid burn-off zones for rapid and efficient removal of the lubricant. This usually entails an atmosphere with a higher oxidation potential, that is, a higher concentration of gases such as steam and carbon dioxide.

Steel parts with defined levels of carbon require that the furnace atmosphere has the correct concentration of carbonizing components, that is, CO, CH_4, and C_3H_8, in order to assure the correct carbon level and its uniform distribution throughout the part. Endothermic atmospheres (mixtures of hydrogen, nitrogen, and carbon monoxide) are used for this purpose.

For some materials, the sintering process must be carefully controlled for developing optimum properties. The following are examples:

- Aluminum alloys are most widely sintered in very low dew point nitrogen
- Tool steels are sintered in a very narrow temperature range to achieve densification through liquid phase sintering without excessive grain growth and carbide coarsening.
- For best corrosion resistance, stainless steels are preferably sintered at high temperature (1180 to 1290 °C, or 2250 to 2350 °F) in low dew point hydrogen or under vacuum, followed by rapid cooling. Sintering in dissociated ammonia increases strength, but corrosion resistance is only modest because of the formation of chromium nitrides and attendant sensitization. Furthermore, the chloride corrosion resistance of sintered stainless steels goes through a minimum at a density of approximately 7.0 g/cm^3, as a result of crevice corrosion due to the presence of pores. Corrosion resistance in acids improves steadily with increasing density.
- Soft magnetic steels are sintered at high temperatures in low dew point hydrogen to reduce their interstitials (carbon, nitrogen, and oxygen) and to maximize the magnetic properties.

The majority of parts require at least some reducing gases in the furnace atmosphere because of the ever present surface oxides on most metal powders, which, without their removal, would interfere with sintering.

As the sintering process is driven mainly by the surface energy of the powder particles, it is evident that a fine powder sinters more rapidly than a coarse powder. This is the reason why metal injection molding (MIM) employs very fine powders, 5 to 20 μm, which under normal sintering conditions shrink to nearly full density.

Sintering theory describes the evolution of the pore structure in terms of solid state atomic transport (diffusion) events. Theoretical approaches are useful for estimating the effects of the many process variables. In the early stage of sintering, bonds form at the particle contacts. During intermediate stage sintering, in the density range of approximately 70 to 92% of theoretical, the rate of sintering decreases, grain growth occurs, and pores become isolated. In the final stage, spherical and isolated pores shrink only slowly by vacancy diffusion to grain boundaries.

In liquid phase sintering, a liquid coexists with the solid phase during part or the entire sintering process. The presence of the liquid, through a solution-reprecipitation process, enables more rapid sintering and much faster densification than is typical for a solid state system. Thus, with a liquid phase sintering system, it is possible to achieve a high sintered density without the use of a fine powder. Commercially, widely used liquid phase sintering systems include bronze (for porous bearings), copper steels, tool steels, cemented carbides, iron-phosphorous and tungsten-nickel.

In activated sintering, a small amount of an additive is used to improve the diffusion rate during sintering. Examples include palladium added to tungsten and hydrogen chloride added to hydrogen atmospheres for sintering iron compacts.

Apart from the development of strength during sintering, a critical property is the control of dimensional change. In the press and sinter technique, the sintering cycle with its many variants is usually controlled to produce close to zero dimensional change. Shrinkage is usually less than 2.5%. This results in dimensional tolerances of approximately +0.07 to 0.10% for 1 in. diameter parts. The tolerances in the axial directions are approximately +0.5% for a 1 in. long part. Sizing can be used to further improve dimensional tolerances. Further improvements by P/M equipment manufacturers and powder producers also will result in further improvements of this important property. Liquid phase sintering typically produces more distortion and liquid phase sintered parts, even when shrinkage is absent, which are often sized to improve the final tolerances of a part.

Sintering Furnaces. Structural parts are typically sintered in continuous belt, pusher, or walking beam furnaces. For economic reasons, batch-type furnaces are often used for refractory metal powder parts and their alloys as well as for cemented carbide compacts. Vacuum furnaces can be used for all of the above. Still other furnaces are used for hot pressing, hot extrusion, and hot forging. Some refractory materials are sintered by directly passing electrical current through them.

Belt furnaces operate up to approximately 1177 °C (2150 °F). They are widely used for sintering the bulk of structural parts. Pusher and walking beam furnaces are operated at temperatures up to approximately 1371 °C (2500 °F), and vacuum furnaces up to 3000 °C (5432 °F). The various heating elements used in these furnaces (nichrome, kanthal, silicon carbide, molybdenum, and graphite) determine the maximum operating temperatures and the atmospheres (reducing, oxidizing, carbonizing, and inert) under which they are used. Most furnaces are designed to contain a preheat and delubrication zone, a hot zone, and a cooling zone, as shown schematically in Fig. 37.

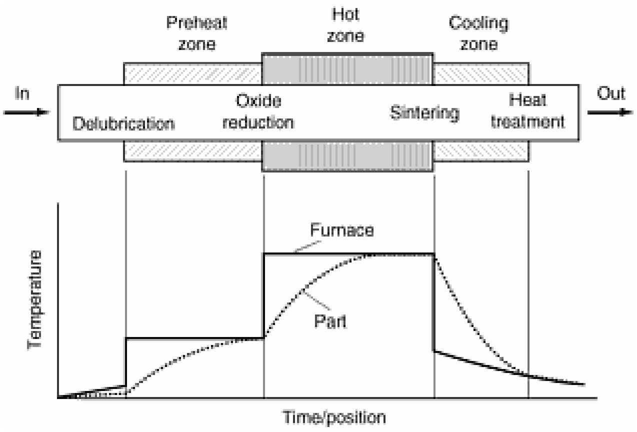


Fig. 37 The sequence of operations occurring in a sintering furnace. The lower diagram shows the time-temperature profile typical of metal powder sintering. Source: Ref 4

Warm Compaction. In warm compaction both powder and die are heated under a protective atmosphere and the compacted. This process produces parts with densities up to approximately 95% of theoretical, that is, similar to those obtained by double pressing, but at a lower cost. Green strength is also significantly higher so that parts can be machined in the green condition.

Full Density Processes

Commercial full density processes include powder forging (P/F), metal injection molding (MIM), hot isostatic pressing (HIP), roll compacting, hot pressing, extrusion, and spray forming. In these processes, porosity is eliminated and physical and mechanical properties are improved to the level of wrought materials and sometimes beyond.

Strengthening a part through alloying additions is less limited in the full density processes than it is in the press and sinter process. In the latter, high compressibility is important to achieve high pressed densities. In P/F, MIM, and HIP, the compressibility of a powder plays only a minor role. It is for this reason that the press and sinter process often employs powder mixtures and relies on alloying during sintering, while the full density processes in general prefer the harder prealloyed powders.

Several of the full density processes offer complex shape capability and attractive advantages regarding material utilization, energy efficiency, and precision, in comparison to conventional wrought materials. These advantages are, however, obtained through the use of more expensive processing. High or full density alone is not sufficient to achieve superior properties. Most full density processes use "clean" powders, and any nonreducible surface oxides are limited to very small amounts and, if present, are broken up and homogeneously distributed through shear deformation. Fully dense P/M materials can exceed the properties of wrought materials of the same composition through control of the microstructure, that is, control of various defects, homogeneity of structure, and the smaller grain size typical of most P/M materials. It is, therefore, important to determine the properties needed in a given application and then select the most economic process that can achieve the desired properties. Full dense processing is currently used to manufacture high fatigue strength structural parts for automotive uses; superalloy components; high-temperature, light-weight composites; wear resistant materials; cutting tools; permanent magnets; and dispersion-strengthened copper.

Figure 38 compares schematically some of the options of high and full density processing with respect to density, part size, and level of performance. The range of properties for a given density (cross-hatched area) arises from alloying and heat treatment effects, as well as from morphological differences. Tables 3 and 4 compare several performance and other properties of the major full density processes.

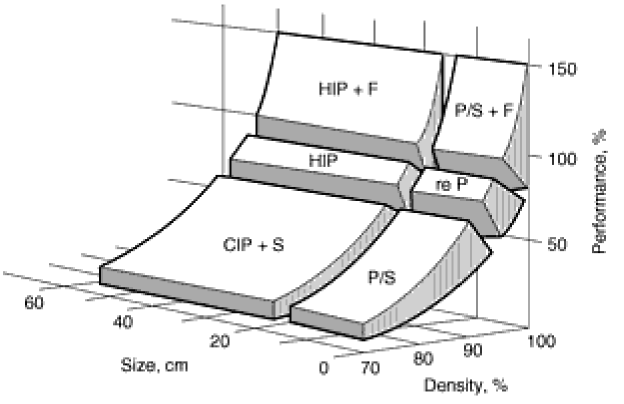


Fig. 38 Three of the variables that influence the selection of a powder metallurgy processing method: component size, density, and performance (as a percentage of that of a wrought material). That behavior corresponds to ferrous based P/M systems formed from coarse powder, but is representative of many powder metallurgy materials. The symbols are press and sinter, P/S; press, sinter, and repress, reP; press, sinter, and forge, P/S + F; cold isostatically press and sinter, CIP + S; hot isostatically press, HIP; hot isostatically press and forge, HIP + F. Source: Ref 4

Powder Forging. In P/F a so-called preform, made by conventional pressing and sintering of a forging grade powder, is forged by a simple blow in a confined die at an elevated temperature (800 to 1200 °C, or 1450 to 2200 °F, for ferrous parts). In hot upsetting, the preform undergoes a significant amount of lateral material flow; in hot repressing, material flow is mainly in the direction of pressing. Hot upsetting with its large amount of shear stresses is effective in breaking up powder particle oxide films, which improves metallurgical bonding between particle interfaces and enhances dynamic mechanical properties. Weight distribution within the preform is carefully controlled to obtain full density without tool breakage. Although P/F involves less handling, fewer dies and processing steps, and produces less scrap than conventional forging of cast materials, it is presently primarily used for the high volume production of automotive parts. This is attributed to the high cost for developing preforms and maintaining forging tools and automated production systems. In hot upsetting, the design of the preform is critical in that densification and shaping through the application of a uniaxial force occur simultaneously and must occur without bulging and cracking of the preform. Forging windows (computer-aided design) describe the amounts of fracture-free permissible straining.

Figure 39 shows a few of the many possible operating layouts of a powder forging process line. For the forging steps, the heated preform is removed from the furnace, usually by a robotic manipulator, and located in the die cavity for forging at high pressure (690 to 965 MPa, or 100 to 140 ksi). The preform can also be coated with graphite to minimize its oxidation during reheating and transfer to the forging die.

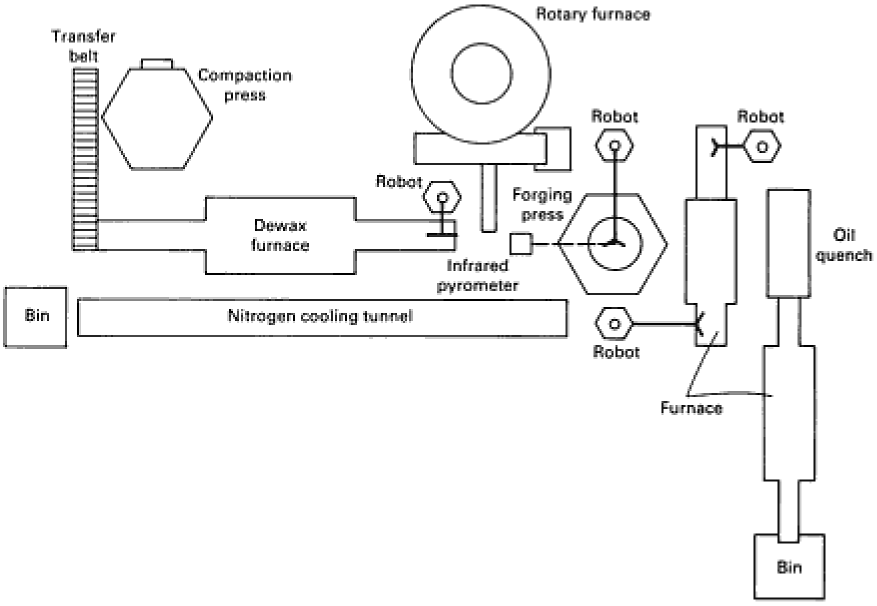


Fig. 39 A powder forging process line. Source: Ref 9

Metal Injection Molding. In MIM, a uniform mixture of metal powder and binder is injected into a mold (Fig. 40), the binder is removed, and the part sintered to more or less full density. This process permits the manufacture of very complex metallic shapes with less expensive forming equipment than the equipment used in the press and sinter process. The powders suitable for MIM are, however, very fine with an average particle size of less than approximately 20 μm, and they can cost over twice as much as the coarser powders used in the conventional press and sinter process. The high surface area of the fine powders provide the surface energy necessary to achieve full densification during sintering. Widely used powders include carbonyl iron and nickel powders and other fine and more or less spherically shaped powders made by other processes. Near spherically shaped powders provide desirable high packing densities. The large amount of binder used in MIM, up to 40%, must be removed carefully through solvent or capillary extraction and/or through thermal debinding. The large amount of shrinkage (20% linear) taking place during sintering is mainly isotropic, and therefore dimensional tolerances, although somewhat inferior to pressed and sintered parts, are acceptable.

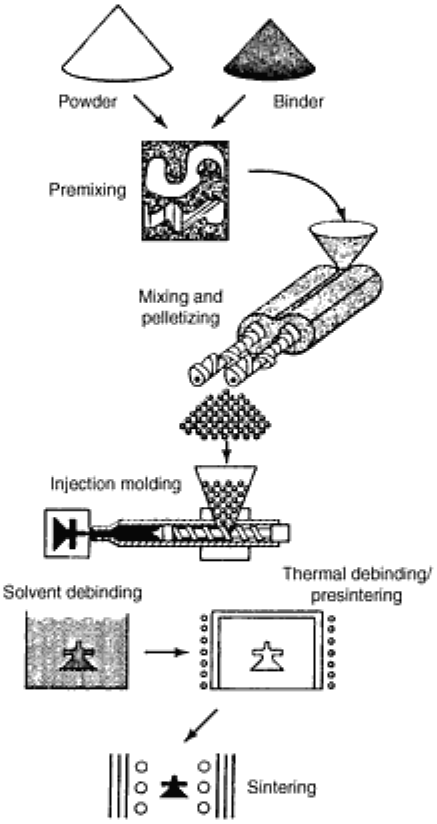


Fig. 40 Schematic of the metal injection molding process. Source: Ref 4

Metal injection molding is mostly used for the manufacture of relatively small parts, usually less than $\frac{1}{4}$ lb, of complex geometries. Typical products include rechargeable batteries, orthodontic brackets, capacitors, filters, and catalytic substrates.

Forming methods that use similar metal powders and binders similar to MIM include various types of slip casting, extrusion, and freeze drying.

Hot Isostatic Pressing. In HIP, or "hipping," a powder is filled into a gas-tight metal or ceramic container and then heated and vacuum degassed to remove volatile contaminants. This is followed by further heating and pressurizing with gas (Ar or N_2) in a HIP vessel. Temperatures up to 2200 °C (4000 °F) and pressures up to 200 MPa (30 ksi) are in use. Because of the isotropic pressure, the consolidated powder is in the shape of the original container except for the smaller size. The container can be stripped from the consolidated part by machining or by chemical dissolution. Hot isostatic pressing allows the production of large parts with very good shape complexity but modest dimensional tolerances and low production rate. The dimensional tolerances are over an order of magnitude inferior to conventional die compaction and to P/F. For these reasons, HIP is mainly used for the consolidation of expensive metals, preferably of large size, such as superalloys, titanium, stainless and tool steels, and composites.

Hot isostatic pressing is also applied to P/M materials with densities over 92%. In this case, no container is necessary because at such densities there exists no open porosity. Cemented carbides, wear materials, and titanium implants are manufactured this way.

Because of the hydrostatic stresses in HIP, powder consolidation occurs with only little shear on the particle surfaces. This mandates the use of very clean and oxide-free powders.

Roll Compaction. In roll compaction or powder rolling, conventional rolling technology is employed to compact a powder at room temperature into a porous (60 to 90% of theoretical) strip. The powder is gravity fed into the gap of two rolls. The flexible green strip enters a sintering furnace followed by hot rolls to complete densification to theoretical density. Roll compaction of powders is used in the manufacture of high purity metals, soft magnetic alloys, composite, and other specialty materials.

Hot pressing can be performed in a rigid die using uniaxial pressure, similar to die compaction. A protective atmosphere protects the powder from becoming oxidized. Alternatively, the powder can be encapsulated in a container. Graphite, refractory metals, or ceramics can be used as die materials. Hot pressing is a slow process because of the large thermal mass of the tooling. Typical maximums for temperature and pressure are 2200 °C (4000 °F) and 50 MPa (7.3 ksi). Hot pressing under vacuum minimizes contamination. Hot pressing is used industrially for the manufacture of diamond tool and friction materials and beryllium.

Extrusion. In extrusion, a powder is typically canned, degassed, and then extruded at elevated temperature (over two-thirds of the absolute melting point of the material. For full densification and crack-free extrusion, reduction rates greater than ten are used. Temperature is the main control variable to achieve good product quality and acceptable tooling life. The high level of shear present in powder extrusion is very effective in breaking up prior particle boundaries of highly alloyed metals. This results in superior microstructures and superior mechanical properties.

Extrusion is used commercially for the manufacture of stainless steel tubing, oxide-dispersion strengthened metals, composites, and other specialty materials.

Spray Forming. In spray forming, inert gas atomized powder is directed onto a substrate. With proper process control, the atomized droplets reach the substrate surface in semisolid condition and splat deform to full or nearly full density. Rapid heat extraction results in minimal segregation in even complex alloys and in very good homogeneity. Deposition rates of up to 2 kg/s are possible. Spray forming is currently being applied to nickel, copper, and aluminum alloys.

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Secondary Operations

Sometimes sintered parts require special treatments, known as secondary and/or finishing operations, to meet final application requirements. They include heat treatments, joining, repressing and sizing, machining, and various kinds of surface treatments. The presence of residual porosity requires special precautions in some of these processes.

Heat treatments serve to increase the surface hardness of a part to improve wear resistance or to increase the hardness of the entire part to improve strength. Powder metallurgy parts with residual porosity are heat treated in carburizing and nitriding gases or in noncorrosive liquids (quench oils). Porosity in P/M parts increases the depth of carburization (Fig. 41). Therefore, parts to be case carburized should have a density of at least 7.2 g/cm^3 to avoid penetration of the carbonizing gas into the part interior. Lower density parts are sometimes copper infiltrated to meet that requirement.

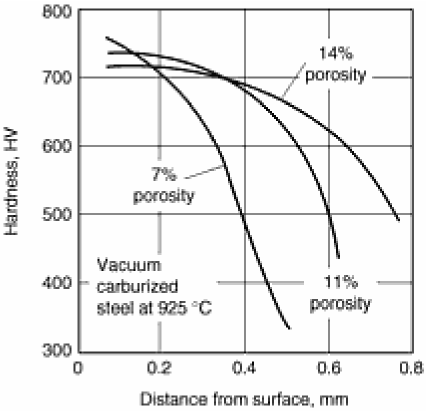

Fig. 41 Hardness, in terms of the Vickers hardness number, versus depth below the surface for three P/M steels following vacuum carburization at 925 °C (1695 °F). The higher the porosity the deeper the carbon penetration because of permeation through the open pore network. Below approximately 8% porosity, the carburization process is largely by solid-state diffusion. Source: Ref 4

The hardenability of P/M parts is reduced due to the presence of pores, which reduce thermal conductivity and cooling rate. This is illustrated in Fig. 42 for two porosity levels. Although manganese and chromium significantly improve hardenability, their use is limited to very low dew point atmospheres, which prevent the oxidation of these elements.

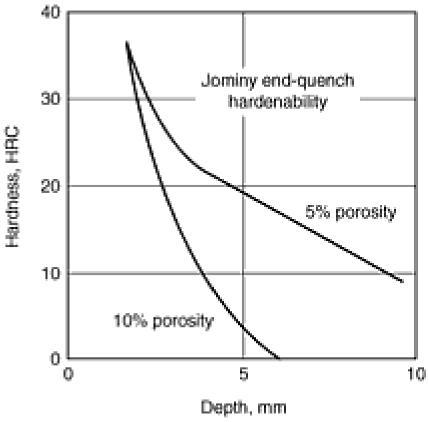

Fig. 42 Hardenability, as measured by Jominy end-quench hardness traces, for two porosity levels in sintered steel. The lower porosity gives better heat conduction with concomitantly greater depth of a high hardness. Source: Ref 4

Porous steel parts can be steam treated to improve wear and corrosion resistance and to provide low-pressure, leak tightness. The treatment is performed at low temperature in superheated steam. The steam oxidizes the surface pores, which close through formation of an adherent layer of bluish to black iron oxide (Fe_3O_4).

Joining. At low porosity levels (<8%), P/M parts can be joined similar to wrought materials. At densities of 80 to 90%, joining techniques based on fusion (welding and brazing) are successful provided the amount of melt is kept low. For lower densities, special brazing alloys have been developed, which minimizes the amount of filler metal penetrating the pore space of a part.

Copper infiltration can be used to sinter, infiltrate, and braze an assembly of several green parts in a simple operation.

Repressing and Sizing. Pressed and sintered parts can be repressed to increase their density and mechanical properties, or just sized to reduce their dimensional variations. Figure 43 illustrates repressing for 316L stainless steel. The latter is commonly done with bronze bearings to eliminate so-called hourglassing distortion.

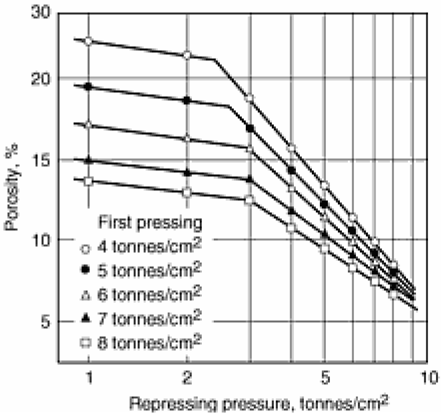

Fig. 43 Effect of repressing pressure on porosity of 316L stainless steel parts pressed from 4 to 8 tonnes/cm^2 and presintered for 15 min at 1050 °C (1920 °F). Source: Ref 10

Machining. Powder metallurgy can be machined to add features not possible with uniaxial pressing, that is, threads, undercuts, and horizontal holes, or to improve dimensions and surface roughness. The presence of pores reduces the heat conductivity of a part leading to heat erosion; it also causes interrupted cutting, which imposes cyclic stresses on the tool, thereby reducing its fatigue life. Copper infiltration and resin impregnation are used successfully for improving the machinability of porous P/M parts.

Powder metallurgy parts requiring machining are often pressed with machinability enhancing additives, such as MnS, MoS_2, Pb, Te, and Sn.

Surface Treatments. Examples of surface treatments used for P/M parts include deburring, plating, polishing, sealing, and shot peening.

Dry or wet tumbling or vibrating P/M parts with or without an abrasive medium removes their surface flashes and burrs that were formed in the pressing operation. Cleaning or washing is often combined with deburring to remove surface contaminants.

Powder metallurgy parts with densities above 83% can be mechanically plated in a tumbling barrel using glass beads, water, and the metal plating powder. Parts with densities above approximately 94% can be electroplated. In lower density parts the pores are closed by impregnation or, if applicable, through burnishing, buffing, or steam treating.

Shot peening is used to improve the fatigue life of P/M parts. The repeated impacts of small diameter shot generate cold worked surfaces with compressive residual stresses.

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Principles and Procedures of Fractography

Introduction

FRACTOGRAPHY is the term coined in 1944 to describe the science of studying fracture surfaces, although fractures and fracture surfaces had been examined and studied for centuries as part of the science of metallurgy. The two chief metallurgical benefits of fractography are that it is a useful tool in failure analysis and it provides a means of correlating the influence of microstructure on the fracture mode of the material.

Study of the characteristics of fracture surfaces by optical (light-microscope) fractography is widely practiced, particularly when a low magnification of the fracture surface is adequate. This study can be accomplished with relatively simple equipment by personnel with moderate training.

Preparation and Preservation of Fracture Specimens

FRACTURE SURFACES are fragile and subject to mechanical and environmental damage that can destroy microstructural features. Consequently, fracture specimens must be carefully handled during all stages of analysis.

Care and Handling of Fractures

Fracture interpretation is a function of the fracture surface condition. Because the fracture surface contains a wealth of information, it is important to understand the types of damage that can obscure or obliterate fracture features and obstruct interpretation. These types of damage are usually classified as chemical and mechanical damage. Chemical or mechanical damage of the fracture surface can occur during or after the fracture event. If damage occurs during the fracture event, very little can usually be done to minimize it. However, proper handling and care of fractures can minimize damage that can occur after the fracture.

Chemical damage of the fracture surface that occurs after the fracture event is the result of environmental conditions present after the fracture. Any environment that is aggressive to the base metal will cause the fracture surface to be chemically damaged. Humid air is considered to be aggressive to most iron-base alloys and will cause oxidation to occur on steel fracture surfaces in a brief period of time. Touching a fracture surface with the fingers will introduce moisture and salts that may chemically attack the fracture surface.

Chemical damage to a fracture can be prevented in a number of ways, and each laboratory has its preferred method. Because the identification of foreign material present on a fracture surface may be important in the overall interpretation of the cause of fracture, many laboratories prefer not to use corrosion-preventive coatings on fractures. If analysis of foreign material on the fracture surface will not be required (for example, in analysis of laboratory-produced fractures), a satisfactory method of preserving the fracture and preventing it from corroding is to apply a coating. When in the field, the fracture can be coated with oil or a good grade of fresh axle grease.

Mechanical damage may arise from several sources, including simply permitting the fracture surface to strike other objects. This can occur during the fracture event (as is often observed in fatigue failures) or in removing a fractured piece from its surroundings or transporting it from one place to another. There is also a tendency for people to put the mating halves of the fracture together; this should be avoided, particularly in view of the microscopic features examined in microfractography. Subtle fracture-surface details are easily damaged.

Cleaning of Metal Fractures

Numerous cleaning procedures have been developed, each suited for a particular metal or the preference of a particular laboratory. Most fractured parts that have undergone extensive exposure to corrosive environmental conditions will typically require some cleaning. The most common techniques for cleaning fracture surfaces, in order of increasing aggressiveness, are:

- Dry air blast or soft organic-fiber brush (artist's brush) cleaning
- Replica stripping
- Organic-solvent cleaning
- Water-base detergent cleaning assisted by ultrasonic agitation
- Cathodic cleaning
- Chemical-etch cleaning

The mildest, least aggressive cleaning procedure should be tried first, and the results should be monitored with a stereo binocular microscope. If residue is still left on the fracture surface, more aggressive cleaning procedures should be implemented in order of increasing aggressiveness.

Because identification of foreign material present on a fracture may be important, many laboratories examine the original fracture surface before and after cleaning. Wire brushes, grinding wheels, rust removing pastes, or similar methods should never be used for cleaning fracture surfaces.

Sectioning of Fractures

It is frequently necessary to remove the portion containing a fracture from the total part (because the total part is to be repaired) or to reduce the size of the specimen to be examined to a size that is convenient to handle.

For large parts, a common method of specimen removal is flame cutting. The cutting must be done at a sufficient distance from the fracture so that the microstructure of the metal underlying the fracture surface is not altered by the heat of the flame and so that none of the molten metal from flame cutting is deposited on the fracture surface.

Saw cutting and cutoff-wheel cutting can be used for parts in a wide range of sizes. Dry cutting is preferable, because coolants may corrode the fracture or may wash away foreign matter from the fracture. A coolant may be required, however, if a dry cut cannot be made at a sufficient distance from the fracture to avoid heat damage.

Often the fracture can be sectioned by hand with a hacksaw. Temperature and corrosion can be kept to a minimum using this method.

Opening of Secondary Cracks

When the primary fracture has been damaged or corroded to a degree that obscures information, it is desirable to open any secondary cracks to expose their fracture surfaces for examination and study. These cracks may provide more information than the primary fracture. If rather tightly closed, they may have been protected from corrosive conditions, and if they have existed for less time than the primary fracture, they may have corroded less. Also, primary cracks that have not propagated to total fracture may have to be opened.

In opening these types of cracks for examination, care must be exercised to prevent damage, primarily mechanical, to the fracture surface. This can usually be accomplished if opening is done such that the two faces of the fracture are moved in opposite directions, normal to the fracture plane. A saw cut can usually be made from the back of the fractured part to a point near the tip of the crack, using extreme care to avoid actually reaching the crack tip. This saw cut will reduce the amount of solid metal that must be broken. Final breaking of the specimen can be done by:

- Clamping the two sides of the fractured part in a tensile-testing machine, if the shape permits, and pulling
- Placing the specimen in a vise and bending one half away from the other half by striking it with a hammer in a way that will avoid damaging the crack surfaces
- Gripping the halves of the fracture in pliers or vise grips and bending or pulling them apart

Effect of Nondestructive Inspection

Many of the so-called nondestructive inspection methods are not entirely nondestructive. The liquid penetrants used for crack detection may corrode fractures in some metals, and they certainly will deposit foreign compounds on the fracture surfaces--both of which could lead to misinterpretation of the nature of the fracture.

Even magnetic-particle inspection, which is often used to locate cracks in ferrous parts, may affect later examination. For example, arcing that may occur across tight cracks can affect their fracture surfaces.

Photography of Fractured Parts and Fracture Surfaces

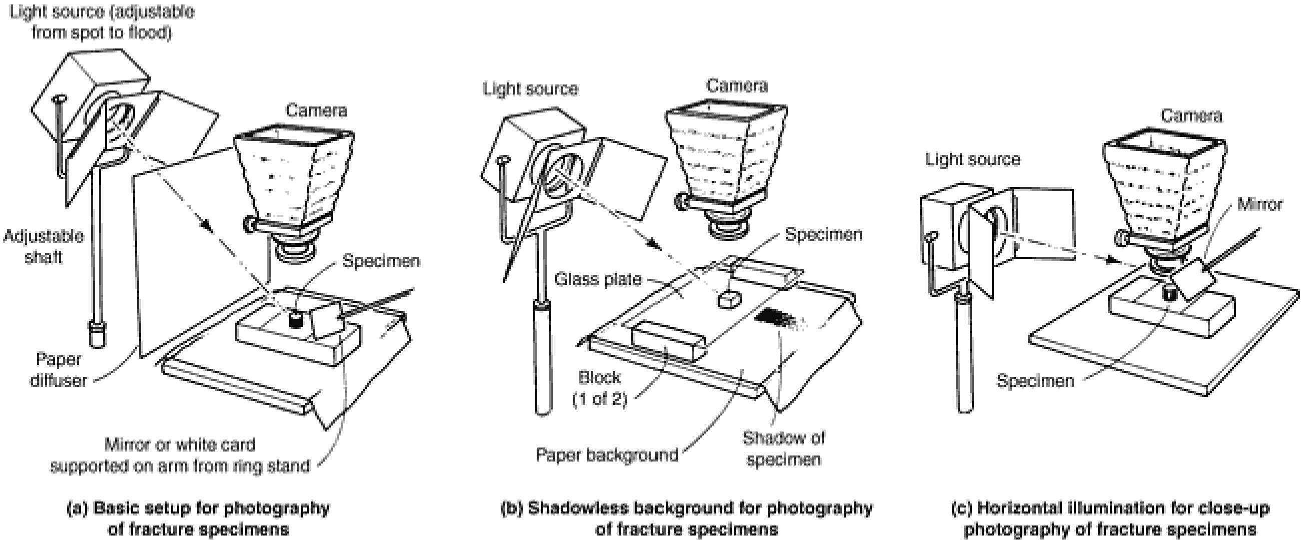
PHOTOGRAPHY of a fracture surface should be preceded by a detailed and thorough examination of the specimen in the as-received condition to determine which features are most important, which aspects are extraneous (such as dirt or postfracture mechanical damage), and whether special treatment of the surface will be required. This scrutiny should begin with unassisted visual examination, continue with inspection with a hand-held magnifier (and with a penlight if helpful), and perhaps include study with a low-power stereomicroscope. Observations made in these surveys should be recorded for future review and determination of the probable causes of fracture. A list should be made of the features deserving photography, with the magnification that will probably be required.

The next step should be general photography of the entire fractured part and of the broken pieces, to record their size and condition and to show how the fracture is related to the components of the part.

Setups for Photography of Fractured Parts

If possible, it is preferable to bring the parts or assemblies into the laboratory for photographing, where factors such as lighting can be carefully controlled. For larger parts, background paper, which is available in white or in colors and in rolls of various widths, can be used to provide an uncluttered background.

A workable setup for photographing specimens and small parts is with a view camera mounted vertically on an enlarger (or equivalent) stand. The longest-focal-length lens that will conveniently give the desired magnification to fill the image area should be chosen. Simple basic setups that should be satisfactory for photographing specimens and most small parts are shown in Fig. 1.



(a) Basic setup for photography of fracture specimens

(b) Shadowless background for photography of fracture specimens

(c) Horizontal illumination for close-up photography of fracture specimens

Fig. 1 Basic setups and lighting used to photograph fracture specimens and small parts. (a) General arrangement of camera, light source with diffuser, and specimen. Size and angle of the beam of light should be adjusted to give the best display of texture. A reflecting mirror or white card can be used to fill in shadows. (b) Placing the specimen on a raised glass plate will throw the shadow beyond the view range of the camera and provide a shadowless background. (c) If the magnification desired requires the close approach of the camera to the specimen, a horizontal light beam reflected by a small mirror positioned near the camera lens will provide

the proper angle of illumination.

Cameras

The camera selected for photographing fractured parts and fracture surfaces should be the one that will do the best job for the major part of the work of the laboratory. There is no one ideal camera.

Microscope Systems. Low-magnification stereo and monocular microscopes with attached cameras are suitable for photography of fracture surfaces. In general, these types of microscopes will cover a much smaller field than is obtainable with the single photographic objective lens. Some systems permit the eyepiece on the microscope to be removed to increase the size of the field.

Whereas view camera systems have practical magnification limits of 15 to 20 diameters, much higher magnifications can be obtained with a microscope, the magnification being limited primarily by the diminishing depth of field at higher powers.

Lighting Techniques

For indoor photography, the usual technique for illumination of a part is to place one light to one side of and above the camera to light the part at a 45° angle, and a second light to the other side, at about camera level, as a fill light. At times, a third light is placed slightly behind the part for backlighting.

Lighting is very critical in photography. The specimen should be placed on a background which will not detract from the resolution of the fracture surface. For basic lighting, one spotlight is suggested. The light is then raised or lowered, and the beam adjusted from flood to spot, to find the quality of lighting desired. Generally, the flatter the fracture surface, the lower the light should be. The effects of the angle of lighting are illustrated in Fig. 2. The angle of the incident light is much more important than its intensity.

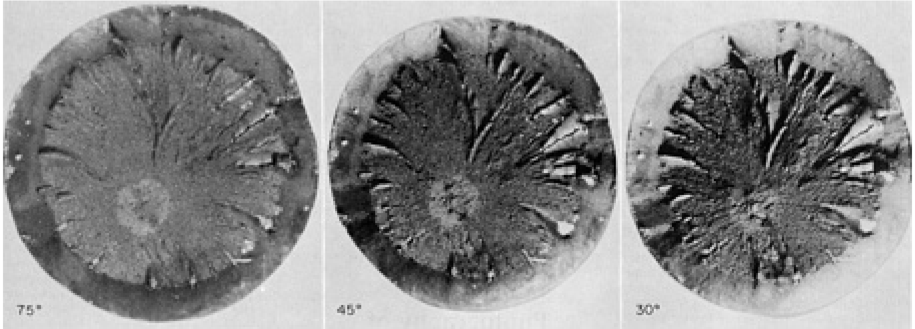


Fig. 2 Light fractographs showing effect of angle of incident light in delineating texture of a fracture surface of an unnotched laboratory tensile-test specimen of 4340 steel. The microstructure was tempered martensite. As the angle of illumination approaches 90°, the surface becomes featureless. The precise optimum angle of obliquity depends on the nature of the fracture markings. 7×

A spotlight beam without a diffuser, or a bare bulb with a small filament, will provide high-contrast lighting. If desired, the light can be diffused by placing a piece of tracing paper between the light source and the specimen.

Film

There are a number of film types that have been used with macrophotographic large-format view cameras, both the traditional wet processed films and instant (Polaroid, Polaroid Corporation, Cambridge, MA) films. Today, increased use is being made of digital, "filmless" photography, and this trend is expected to increase. Historically, wet-processed black and white and color films have been used to document fractures and other failed components. Their advantages are ease of reproduction, highest quality of images, and a wide selection of film types and formats. Their disadvantage centers around the need for a darkroom (practical only for large companies) or a commercial laboratory to process the film and make prints. This is labor-intensive but does produce the highest quality images.

Traditional wet-processed panchromatic films, available through a number of sources, such as the Eastman Kodak Co. (Rochester, NY) are available in a vast range of types, formats, and sizes. Black and white films that are particularly well suited for macrophotography include, but are not limited to: Kodak EKTAPAN (ISO 100, daylight or tungsten, very fine grain, 4 × 5, 5 × 7, or 8 × 10 in. negatives), PLUS-X Pan Professional film (ISO 125, extremely fine grained, 4 × 5, 5 × 7, and 8 × 10 in. negatives), T-MAX 100 Professional film (ISO 100, extremely fine grained, 4 × 5, 5 × 7, 8 × 10, and 11 × 14 in. negatives), and TRI-X Pan Professional film (ISO 320, fine grained, 2.25 × 3.25, 4 × 5, 5 × 7, and 8 × 10 in. negatives). Many of these films are also available in 35 mm format, which is frequently used in photomacrography.

Since the 1960s, Polaroid instant films have become widely used in metallographic laboratories due chiefly to the increased speed of obtaining prints and the reduction in manpower to produce them. Today, there are a host of panchromatic film sizes and types available. Most commonly, metallographers use 4 × 5 in. sheet or pack films. Other common sizes are 3.25 × 4.25 in. and 8 × 10 in. Type 52, a fine-grained black and white print film that must be coated, is the most commonly used 4 × 5 in. sheet film. Its ISO speed is 400, and it has a good contrast range. However, if multiple prints are required, additional prints must be made. Only with type 55 is a negative produced. This film has an ISO speed of 50, and it is fine grained with a wide contrast range. Type 52 can be obtained in film packs, as type 552, also at 400 ISO. There is a similar coaterless 4 × 5 in. film available as type 53 in individual sheets or as type 553 in film packs. It has an ISO speed of 800, and the images are nearly as good as with types 52 or 55 films. There are also higher speed black and white films that are used mainly in low-light-level situations. These are types 57 (4 × 5 in. sheet) and type 667 (3.25 × 4.25 in. film packs) with an ISO speed of 3000. Neither require coating.

Any copies made photographically should be made at the aperture providing the best resolution at 1×. The setting will typically be *i*/22. Original exposures using Polaroid type 55 P-N (50 ISO film speed) will be eight times longer than with type 52 but will produce a high-quality negative. For an optimum-quality negative, the exposure giving the best quality Polaroid print should be doubled. The 55 P-N negative material has finer grain and higher resolution than the 125 ISO speed black and white film commonly used in 35 mm cameras.

For color work, which is sometimes required to document colored features on fractures or other specimens (e.g., corrosion products), there are a variety of wet-processed color films in a variety of formats. Both color negative films and color reversal films are available, the former are more popular for macrophotography. Popular color negative films for macrophotography include, but are not limited to: Kodak Pro 100 film (ISO 100, fine grained, 4 × 5 and 8 × 10 in. negatives), Pro 100T film (ISO 100, 64, or 40 (depending upon exposure time), tungsten balanced, fine grained, 4 × 5, 5 × 7, and 8 × 10 in. negatives), and VERICOLOR III Professional film (ISO 160, daylight or flash, 4 × 5, 5 × 7, and 8 × 10 in. negatives). There is a similar line of film products in the Ektachrome line (Eastman Kodak Co., Rochester, NY) that uses the E-6 process rather than the C-41 process. Also, most of these films are available in the 35 mm format.

In the instant film category, a number of color films are used regularly. Polacolor 64T (tungsten) is available in both 4 × 5 in. individual sheets and as 3.25 × 4.25 in. film packs. The film is balanced to use with tungsten lamps (3000 K), which are often used for indoor lighting and with metallographs. This film handles reciprocity losses very well. The other films are balanced for daylight and include types 59 (4 × 5 in. sheets, ISO 80), type 559 (4 × 5 in. film pack, ISO 80), type 669 (3.25 × 4.25 in. film packs, ISO 80), and type 809 (8 × 10 in. sheets, ISO 80). A comprehensive treatment of film selection, light filtration, processing, and printing is provided in ASTM E 883 ("Standard Practice for Reflected-Light Photomicrography").

Digital photography requires a suitable camera, generally a charge-coupled device (CCO) type, either color or black and white (the latter has better resolution as a function of cost), a computer and frame grabber (unless a digital camera is used), appropriate software and storage devices, and a suitable printer. This approach has many merits, such as ease of storage and retrieval of images, flexibility in image size, ease of reproducing images, ability to annotate images with text and arrows, and elimination of cutting and gluing prints into reports. Digital photography is not necessarily faster than instant photography, and the initial equipment cost is not trivial. For laboratories that do considerable photomacrography, however, this approach has many virtues. On the down side, it is expensive to keep systems technologically up to date, the cost of a high-quality printer is substantial, and the cost per print (for high-quality prints) can vary substantially depending upon the paper required by the printer. A number of metallographic supply houses now offer turnkey systems for digital photomacrography and photomicroscopy.

Stereo Views

Stereo-pair photographs of fracture surfaces provide a means of viewing the fracture contours in simulated three dimensions. The basic technique for preparing such photographs entails taking two pictures of a subject area, the second from an angle slightly different from the first. The photographs are then examined under a visual condition in which, for example, the viewer's left eye focuses on the first picture and his right eye focuses on the second. Stereo viewers are available, and in most cases are necessary, to ease the task of viewing stereo pairs. The effect is to convince the brain that the eyes are indeed seeing a three-dimensional scene. If the angular displacement between the two pictures is appropriate (an included angle of 12° or 14° is desirable), the illusion is very vivid.

Stereo images by light microscopy have been used only to a limited extent because of the restricted depth of field. They provide a useful means of studying fractures at magnifications generally not greater than 200×.

Stereo-pair photographs can be taken using a single-lens camera, if it is provided with a mount that will pivot about a horizontal axis through the subject. After the subject is properly aligned beneath the camera with the mount vertical, the camera is swung to an angle of 6° to 7° from vertical and an exposure is made. The second exposure is made with the camera at the same angle as for the first exposure, but swung to the other side of the vertical, or zero, position.

With the stereomicroscope shown in Fig. 3, it is possible to observe the voids that are a part of ductile dimpled fracture, and, in brittle fractures, cleavage facets and some of the river marks can be discerned. It is most useful for preliminary examination of fracture surfaces, leaving final documentation of fine details for scanning electron microscopy.

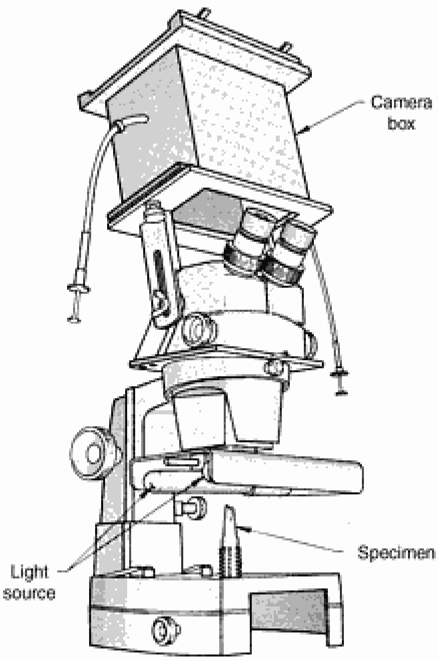


Fig. 3 Optical stereomicroscope with camera box partly removed for direct viewing. The light source is two 40 watt incandescent tubes above the specimen.

An example of a light-microscope stereo pair is shown in Fig. 4. The subject is a fracture surface in a low-carbon steel casting that cracked along prior austenite grain boundaries during a straightening operation. The bold relief contours of the columnar fracture are evident when viewed in stereo.

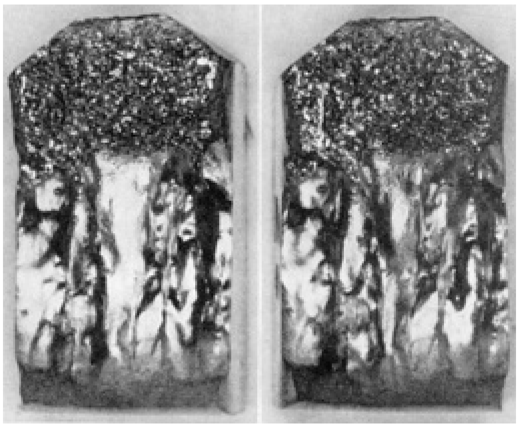


Fig. 4 Stereo view of a fracture surface of cast experimental low-carbon steel. The smooth columnar contours in the lower portions of the photographs were the result of cracking along prior austenite grain boundaries during straightening. The upper portions of the photographs also show intergranular fracture, but along ferrite grain junctions, produced by impact in the laboratory to expose the original crack surface. Light fractograph (stereo pair). 3×

If a tool such as a parallax bar is used, quantitative measurements of topographic depths and elevations can be obtained.

Fractographic Features Revealed by Light Microscopy

THE MACROSCOPIC APPEARANCE of a fracture surface has often been used to appraise the degree of ductility and of toughness present in a metal. According to the concepts of fracture mechanics, toughness is the critical material property associated with overload or rapid fracture. The fracture surface contains vestigial marks that indicate the amounts of high-energy (ductile, or tough) and low-energy (brittle) crack extension that produced the fracture.

Tensile-Fracture Surface Marks in Unnotched Specimens

Tensile-fracture surface marks have been classified into three zones by configuration: the fibrous zone, the radial zone, and the shear-lip zone. This shear-lip zone is the highest-energy portion of the fracture. The relative amount of shear lip provides an indicator of the toughness of the material. The three zones are shown in Fig. 5. Fractures consisting solely of one zone occur only under conditions of extreme ductility or brittleness.

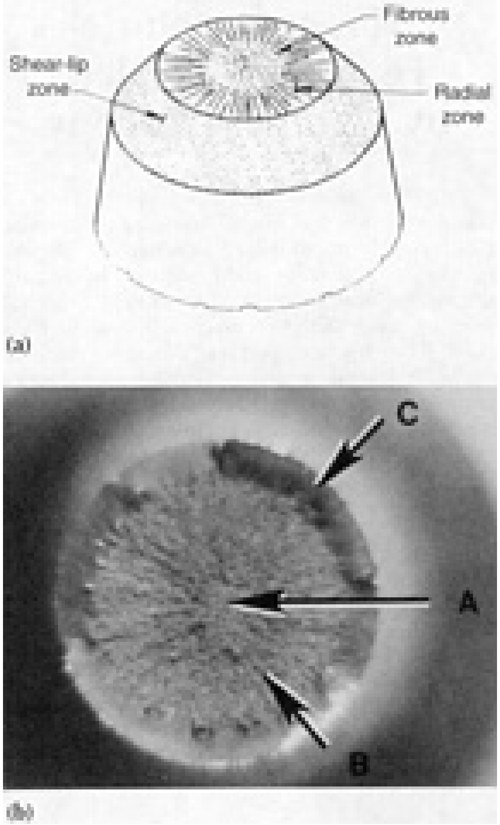


Fig. 5 Tensile-fracture surface marks. (a) Schematic representation of zones within a typical tensile fracture of an unnotched cylindrical specimen. The surfaces of the fibrous and radial zones are usually normal to the tensile axis, as shown. The shear-lip surface is always at about 45° to the tensile axis. (b) Fracture surface of a 4340 steel tensile specimen showing fibrous zone (A), radial zone (B), and shear lip (C). 3×

Fatigue Marks

The formation of cracks under conditions of repeated or cyclic stress has been denoted as fatigue cracking. Zones of crack propagation on fatigue fractures exhibit several types of surface marks, such as beach marks, striations, and ratchet marks.

Beach Marks. The term "beach mark" describes the macroscopic features present on the fracture surface as illustrated in Fig. 6. Beach marks indicate a local region of variation in crack-growth rate. Such beach marks may, but do not always, indicate fatigue as the mode of cracking. Stress-corrosion fractures may also show beach marks.

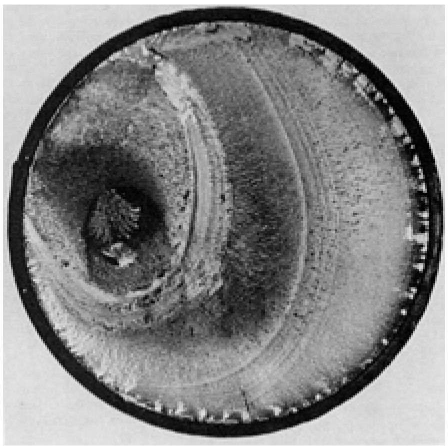


Fig. 6 Fatigue-fracture surface of an AISI 1050 shaft (35 HRC) subjected to rotating bending. Numerous ratchet marks (small shiny areas at surface) indicate that fatigue cracks were initiated at many locations along a sharp snap-ring groove. The eccentric pattern of oval beachmarks indicates that the load on the shaft was not balanced. The final rupture area is near the left (low stress) side, where there may have been no fatigue action.

The presence of beach marks is fortuitous, at least for the investigator, because beach marks permit the origin to be easily determined and provide the analyst with other information concerning the manner of loading, the relative magnitude of the stresses, and the importance of stress concentration (see Fig. 6).

Striations. The term "striation" refers to a "line" on the fracture surface indicating the position of a crack front after an increment of crack propagation has occurred. Each increment of propagation is due to a cycle of stress, i.e., a cyclic load. The distance between striations indicates the advance of the crack front during each succeeding cycle. Fatigue striations are not readily resolvable with the light microscope and are best viewed using a scanning electron microscope (see the section "Interpretation of Scanning-Electron Microscope Fractographs").

Ratchet marks are macroscopic features that may be seen on fatigue fractures in shafts and flat leaf springs, and they may also occur in ductile fractures in overtorqued fasteners. In fatigue fractures, ratchet marks are the result of multiple fatigue-crack origins, each producing a separate fatigue-crack zone (Fig. 6). As two approaching cracks meet, a small step is formed. The small steps are the ratchet marks.

Although ratchet marks are most apparent on the peripheries of fractures in shafts, the stepped appearance is characteristic whenever fatigue cracks emanate from several origins and subsequently meet to form one principal crack front.

Discontinuities

Fractures originate from a broad variety of discontinuities within the metal structure, such as laps and seams from primary metal forming, shrinkage and gas cavities in cast structures, hot tears, inclusions, segregation of impurities, and imperfections in welds. Many of these features are illustrated in the section "Discontinuities Leading to Fracture" in the article "Use of Fractography for Failure Analysis."

Interpretation of Optical Fractographs

A RUDIMENTARY KNOWLEDGE of how to "read" a fracture surface must be gained so that meaningful fractographs can be taken from which to describe the fracture process. Fractography can provide information about the conditions of stress, the effects of temperature and chemical environment, and the origin of the fracture and how the crack progressed to final rupture.

States of Stress

Information regarding the stresses that caused a fracture can be learned from a casual examination of the fractured part.

In many types of fracture, the general plane of fracture is perpendicular to the maximum principal tensile stress. These types, called group I fractures in the following discussion, include cleavage and other brittle fractures, ductile fractures (also called microvoid coalescence and dimpled rupture) under plane-strain conditions (in thick sections), fatigue fractures (at least in the intermediate stages), and stress-corrosion cracks.

Other types of fracture propagate along planes of maximum shear stress. These types, called group II fractures here, include ductile fractures under plane stress (that is, in thin sections or near free surfaces), shear fractures, and the very early stages of fatigue fractures in pure or relatively impurity-free metals. In a ductile material, the shear stresses cause considerable deformation prior to fracture, although the deformation is not always obvious because the shape of the part is not changed except for flow on the surface. Figure 7(a) is a photograph showing deformation in a fractured shaft. Torsional single-overload fractures (group II) of a ductile material usually occur on the transverse shear plane, straight across the cylinder, and exhibit a telltale swirled appearance (Fig. 7b). The final-fracture area will be at the center of the bar. A brittle material in pure torsion will fracture in a plane perpendicular to the tensile-stress component, which is 45° to the specimen axis (group I fracture). A spiral-type fracture is one characteristic of this type of loading and material and can be demonstrated by twisting a piece of chalk to fracture (Fig. 8). The elastic-stress distribution in pure torsion is maximum at the surface and zero at the center. Thus, fracture normally originates at the highest-stressed region (the surface) in pure torsion. Longitudinal torsional fractures are sometimes observed (for example, Fig. 9) because longitudinal planes have the same magnitude of shear stress as transverse planes, and longitudinal planes usually have lower toughness, due to the shape and distribution of inclusions.

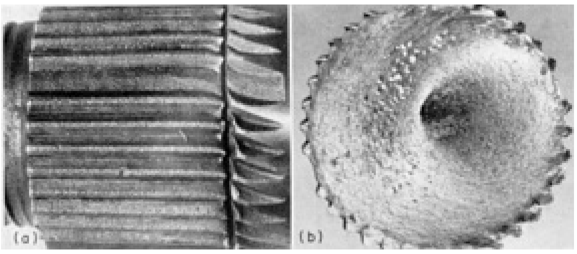


Fig. 7 Splined shaft of 6118 steel that fractured from a single torsional overload. (a) Photograph (~2×) of the shaft showing the deformation of the splines in the region of fracture, which would not occur if the fracture were caused by fatigue. The shaft, 28 mm ($1\frac{3}{32}$ in.) in diameter, was made of 6118 steel and had a hardness of 23 HRC. Being made of a ductile metal, it was twisted in pure torsion with a single overload, yielding the fracture on the transverse shear plane shown in (b). (b) Fracture surface of the shaft, showing the rotary deformation characteristic of a single-torsion-overload fracture in a ductile metal. If there is a combined bending component, the region of final, fast fracture will be offset from the center of the section. This type of fracture should not be confused with one resulting from rotating-bending fatigue, which does not have the gross distortion seen here. Light fractograph. 2×

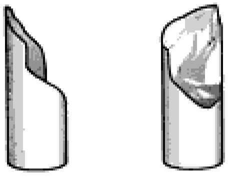


Fig. 8 Torsional brittle fracture of chalk. Fracture follows the 45° direction of maximum tensile stress.

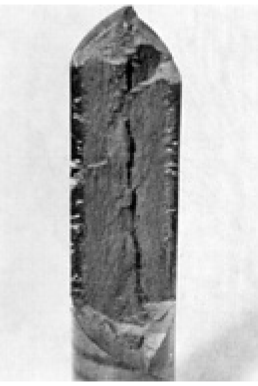


Fig. 9 A torsional-fatigue fracture in an induction-hardened 1037 steel shaft 25 mm (1 in.) in diameter that finally fractured in longitudinal shear. No clear point of origin is visible because the surfaces rubbed as the crack propagated. Light fractograph. ~0.95×

Crack Origins

An interest in the exact location of the point of origin of a fracture derives from the importance of determining what initiated the fracture. The initial examination of a fracture is concerned with the recognition of all features that may point to the crack origin.

Gross Aspects of Fractures. Some indications of crack-propagation direction can be seen by examination of the gross aspects of a broken part. They relate to the order in which events occured, sometimes called "fracture sequencing." The fragments of a fractured structure can be reassembled in approximate juxtaposition, without allowing the fracture surfaces to touch, and then the telltale indications should be sought.

First, a fast-running crack in sheet or plate will frequently branch as it propagates but will almost never join another crack to continue as a single crack. Second, if a running crack joins a pre-existing fracture, it will usually meet it at approximately a 90° angle, not at a shallow angle. Third, it is almost impossible for an intersecting crack to cross and propagate beyond a pre-existing fracture. These considerations lead to the following useful guidelines concerning crack origins:

- The direction to the crack origin is always opposite to that of crack branching, as shown in Fig. 10.
- If a crack meets another at about 90°, it occurred later and the origin should not be sought in it but in the earlier crack. This is known as the T-junction method of crack-origin location (Fig. 11).

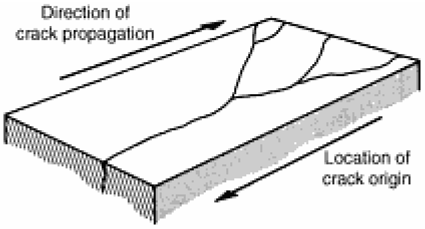


Fig. 10 Schematic representation of the information conveyed by crack branching with regard to the location of the crack origin

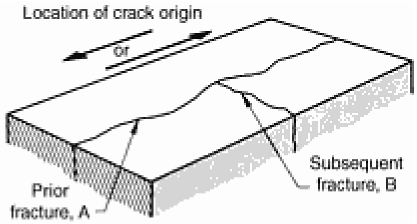


Fig. 11 Schematic representation of the T-junction method of determining which fracture surface to search to locate the crack origin. Because B does not cross A but meets it at about 90°, B occurred later and cannot contain the crack origin.

The initial section of fracture (containing the crack origin) transfers its original load to adjoining sections, in all probability overstressing them. If these sections do not contain imperfections, succeeding fractures (assuming a normally ductile material) will be preceded by a certain amount of plastic deformation.

Fibrous marks, tear ridges, and beach marks can also indicate the location of a crack origin. Chevron markings also can be used. Where the curvature of such marks is slight, the origin is generally on the concave side of the crack-front curve.

In general, the region of crack initiation will be flat and will lack any free-surface shear-lip zone. The shear-lip zone appears only at some distance from the origin and becomes larger as the distance increases (see Fig. 12).

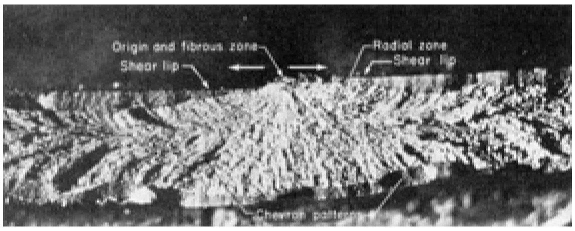


Fig. 12 Fracture in a welded pressure vessel of 4340 steel displaying a flat origin at the top with a shear lip beginning on either side of it. The shear lip increases in width with increasing distance from the origin. The radial marks below the origin and the chevron patterns to the left and right also indicate the directions of fracture. Light fractograph. 6×

Location of Origins in Impact-Overload Fractures. Figure 13 shows the fracture of a 12% Cr steel bar that was notched and then struck with a hammer. Two blows were necessary to complete the fracture. The fracture marks are radial. They may be traced downward to a common intersection. Also present are crack arrests, one at A and a second at B, where fracture progress came to a complete halt before the second blow was struck. The arrest marks are parallel to the crack front, and lines drawn normal to them should intersect at or near the origin. The contours of the final fracture marks, at C and D, also point to the general location of the beginning of fracture.

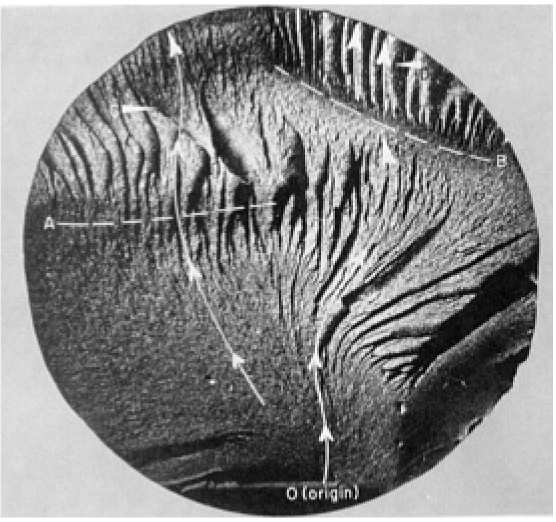


Fig. 13 Locating the origin in an impact fracture, produced by two hammer blows, in a notched bar of 12% Cr steel. Fracture origin can be found in three ways: by tracing the radial marks in the lower portion of the fracture to their point of convergence (the arrows on the curved lines indicate the direction of crack propagation); by drawing normals to the crack-arrest fronts labeled A and B; and by projecting the tangents to the final radial marks at C and D toward the bottom. The crack came to a full stop at B with the first hammer blow and resumed motion at the second hammer blow. Light fractograph. 3×

Fracture Progress

Many types of fractures, including most service fractures, occur by a sequence involving crack initiation, subcritical crack propagation (due to ductile crack extension, fatigue, corrosion fatigue, stress-corrosion cracking or hydrogen embrittlement), and fast fracture, which occurs when the remaining cross section can no longer support the applied load. The fracture processes leave telltale marks on the fracture surfaces, which enable a trained investigator to locate the initiation sites, to discern the propagation direction and crack-front shape, and to distinguish the fast-fracture zone. This information can lead to an understanding of the stress levels and conditions leading to fracture

Fracture Changes During Crack Propagation

Several influences may affect the growth of a crack, causing it to progress thereafter by a mechanism of fracture different from that in effect when cracking started. These influences include local differences in microstructure; changes in stress-intensity factor, *K*; changes in chemical or thermal environment: differences in stress state.

Changes Caused by Local Differences in Structure. Microstructure exerts a pronounced influence on local fracture appearance. The presence of two or more types of microstructure may result in different fracture mechanisms being involved and a different fracture appearance. A simple example is a fracture in a chilled white iron part. Fracture is by cleavage through the chilled zone and is fibrous in the pearlitic zone.

Another structure difference is that of case and core in carburized, flame-hardened, and induction-hardened parts. The difference in properties between such structures can cause a crack to proceed by quite different fracture mechanisms in adjacent regions.

Changes Caused by Altered Environments. A fracture-mechanism change as a result of different chemical and stress environmental conditions is shown in Fig. 14. A corrodent generated small pits below a layer of chromium plate and provided the environment for the growth of stress-corrosion cracks, which originated at the pits. The stress may have been residual or applied. As the stress-corrosion cracks grew, the stress intensity at the crack tip increased for the applied cyclic loads. At some critical level of environment and cyclic-stress intensity, the fracture mechanism changed to one of fatigue. The fatigue cracks propagated until the critical crack-tip stress-intensity values were reached, and then unstable fracture occurred in an essentially ductile manner.

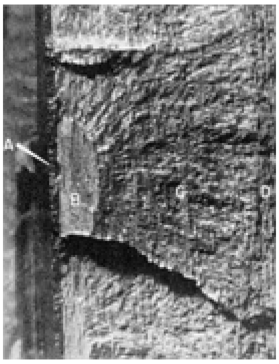


Fig. 14 Changes in fracture mechanism and appearance that were caused by changes in chemical and stress environment for a chromium-plated aluminum alloy 7079-T6 forging. Small corrosion pits formed beneath the layer of chromium plate, as at A, and generated stress-corrosion cracks B. Growth of these cracks altered the stress intensity at the crack tips, leading to propagation of fatigue cracks C. Final, fast fracture D occurred when the critical crack-tip stress-intensity value was reached. Light fractograph. 5.7×

Interpretation of Scanning-Electron Microscope Fractographs

AT LOW MAGNIFICATIONS, the features in scanning electron microscope (SEM) fractographs strongly resemble the aspects of the fracture apparent to the naked eye; but at high magnifications, more detail is visible which needs to be categorized and interpreted if the fractograph is to be related to the micromechanisms of fracture that were active.

It is important to realize that microscopic features of fractures ordinarily differ widely within a small area. The principal categories of fracture features (or fracture modes) are as follows:

- Cleavage features (tongues, microtwins, and location of cleavage-crack origins)
- Quasicleavage features
- Dimples from microvoid coalescence
- Tear ridges
- Fatigue striations

- Separated-grain facets (intergranular fracture)
- Mixed fracture features, including binary combinations of cleavage features, dimples, tears, fatigue striations, and intergranular-fracture features
- Features of fractures resulting from chemical and thermal environments

Transgranular Cleavage Features

In cleavage fracture, the fracture path follows a transgranular plane that is usually a well-defined crystallographic plane. This plane of fracture is one of the {100} planes in most body-centered-cubic metals. Cleavage fracture is produced, usually at low temperature, under a condition of high triaxial stress--that is, at the root of a notch--or at a high deformation rate, as, for example, by impact loading, or as a result of environmental factors.

Figure 15 provides three views, at increasing magnification, of an area in an impact fracture exhibiting features that are typical of cleavage. It is apparent that the fracture plane changes orientation from grain to grain. As a result, the average grain size can be measured on the fractograph and related to grain-size measurements on a metallographic section. The change of orientation from grain to grain leads to a branching of the crack along different planes and to a very chaotic overall appearance of the fracture surface. At higher magnification, many features typical of cleavage can be identified. In Fig. 15(b), the evidence of change in orientation between grain A and grain B is particularly clear because of the river patterns that begin in grain B at the interface. The river patterns, which represent steps between different local cleavage facets of the same general cleavage plane, are well defined.

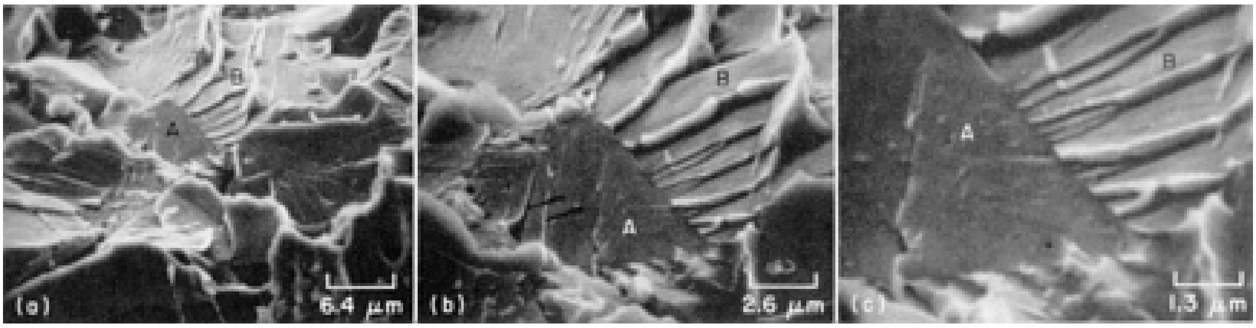


Fig. 15 Cleavage fracture in a notched impact specimen of hot-rolled 1040 steel broken at -196 °C (-321 °F), shown at three magnifications. The specimen was tilted in the scanning electron microscope at an angle of 40° to the electron beam. The cleavage planes followed by the crack show various alignments, as influenced by the orientations of the individual grains. Grain A, at the center in fractograph (a), shows two sets of tongues (see arrowheads in fractograph b) as the result of local cleavage along the {112} planes of microtwins created by plastic deformation at the tip of the main crack on {100} planes. Grain B and many other facets show the cleavage steps of river patterns. The junctions of the steps point in the direction of crack propagation from grain A through grain B, at an angle of about 22° to the horizontal plane. The details of these forks are clear in fractograph (c).

Quasicleavage Features

In steels that have been quenched to form martensite and then tempered to precipitate a fine network of carbide particles, the size and orientation of the available cleavage planes within a grain of prior austenite may be poorly defined. True cleavage planes have been replaced by smaller, ill-defined cleavage facets, which usually are initiated at carbide particles or large inclusions. The small cleavage facets have been referred to as quasicleavage planes, because, although they look like cleavage planes with river patterns radiating from the initiation sites, until recently they have not been clearly identified as crystallographic planes. Quasicleavage features tend to be more rounded, indicating a somewhat higher energy absorption than that of true cleavage.

Quasicleavage facets on a fracture surface of a quenched and tempered 4340 steel specimen broken by impact at -196 °C (-321 °F) are shown in Fig. 16. The poorly defined cleavage facets are connected by tear ridges and shallow dimples.

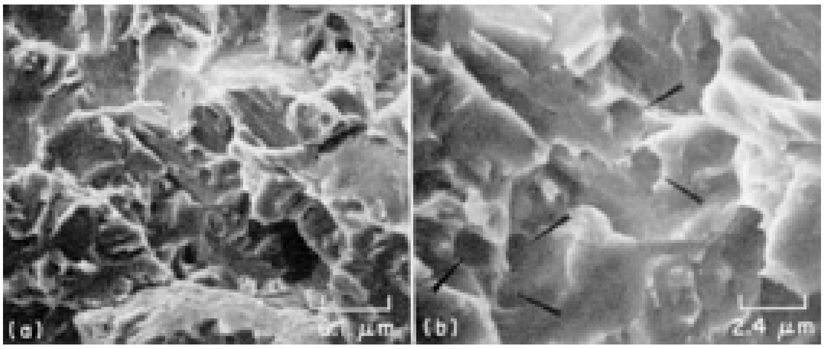


Fig. 16 Quasicleavage in the surface of an impact fracture in a specimen of 4340 steel. The same area is shown in both fractographs, but at different magnifications. The small cleavage facets in martensite platelets contain river patterns and are separated by tear ridges. Shallow dimples, marked by arrowheads, are also visible. Direction of crack propagation is from bottom to top in each fractograph. The specimen was heat treated for 1 h at 843 °C (1550 °F), oil quenched, and tempered for 1 h at 427 °C (800 °F). Fracture was by Charpy impact at -196 °C (-321 °F).

Quasicleavage, or cleavage in complex microstructures, is more difficult to identify than the cleavage found in low-carbon steel made up of ferrite and pearlite. When identification is uncertain, it is essential to relate the fracture features to the microstructure, including the prior austenite grain size, the martensite plate size, and the distribution, size, spacing, and volume fraction of fine carbide particles precipitated during tempering.

Dimples Formed by Microvoid Coalescence

If the temperature of fracture is raised from very low (for example, liquid-nitrogen temperature) to higher levels, the fracture mechanism changes from brittle or cleavage fracture to ductile fracture by microvoid initiation, growth, and coalescence. At low magnification, the fracture surface may exhibit both fibrous and cleavage regions. Fibrous regions are usually observed near the free surface in a shear-lip zone or at the origin of fracture at the center of a smooth (unnotched) tensile specimen. Cleavage regions are typically observed in the surfaces of flat, plane-strain fractures and in regions of high crack velocity. However, at high magnification, the fibrous-fracture region, and also the cleavage region, may show successive fracture mechanisms--that is, the fracture features may include both cleavage facets and dimples. Both dimples and cleavage facets are visible in the Charpy impact fracture shown in Fig. 17. An overall view of the region of transition between ductile and cleavage fracture is shown in Fig. 17(a). The upper portion of the fracture surface in this view is a result of cleavage, and the lower portion is a result of fracture by microvoid coalescence. The cleavage facets in Fig. 17(a) and 17(b) are at a considerable distance from the notch, which is below the region shown in the fractograph. In the intermediate-magnification view of the region of microvoid coalescence (Fig. 17c), facet A cannot be positively identified as a cleavage-fracture feature; it could be the result of a fracture along a grain boundary, or even possibly a microvoid surface that has stretched. Around this facet is a region of ductile fracture, which originated at the interface between the matrix and a carbide particle (in the deep dimple).

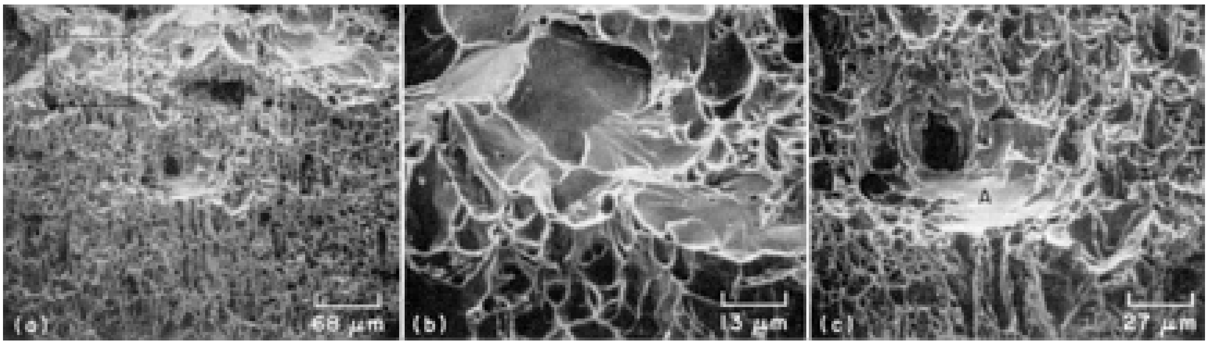


Fig. 17 Dimples and cleavage facets exhibited in three aspects of a Charpy impact fracture at room temperature in a specimen of hot-rolled 1040 steel, tilted in the scanning electron microscope at an angle of

30° to the electron beam. The machined notch of the specimen was below the region shown in (a). The overall direction of crack propagation was upward. Although equiaxed dimples pre-dominate, certain grain orientations near the top of (a) were unfavorable for ductile fracture by microvoid coalescence and local cleavage occurred, as shown in detail in (b), which is a higher-magnification view of the outlined area in (a). Fractograph (c), a higher-magnification view of the region at the center of (a), shows a deep dimple, which initiated the local ductile fracture immediately surrounding it. The smooth surface at A shows no river patterns and should not be identified as a cleavage facet; it could be a grain-boundary surface, or perhaps a region of stretching.

Tearing

Tearing designates a mechanism of local fracture that is often found at a discontinuity in the crack advance by another fracture mechanism. It occurs when small regions or ligaments fracture by plastic flow or necking. Tearing is frequently observed when small unbroken areas remain behind the main crack front. The occurrence of tearing is accompanied by the formation of tear ridges, which are typically sharp and thus produce bright contrast in the SEM image. Tearing may also produce flat-topped, featureless areas having some of the characteristics of local glide-plane decohesion, similar to facet A in Fig. 17(c).

Fatigue Striations

The advantages offered by the use of the SEM include:

- Easier identification and evaluation of the origin of the fatigue fracture, whether near a free surface, at an edge, or at the bottom of a notch or a groove
- Better differentiation between stages I and II of fatigue-fracture progress by viewing the overall fracture at low magnification not obtainable with a transmission electron microscope
- Estimates of crack-growth rates, which are used in fracture mechanics evaluation of loads or for estimation of total number of cycles to failure
- Simpler quantitative analysis of fracture surfaces to determine which portions of fracture surfaces resulted from microvoid coalescence, from intergranular separation, and from cleavage fracture.

The main disadvantage of scanning electron microscopy for the investigation of fatigue fractures is that fatigue striations are not as sharply defined as with transmission electron microscopy. This lack of resolution occurs because a striation represents only a small surface displacement, which often fades out in the electron image. By shadowing the fracture surface with a gold-palladium film 10 nm (0.4 μin.) thick, it is possible to enhance striation contrast markedly. Striation spacings as small as 25 nm (1.0 μin.) have been measured in aluminum alloys with the SEM. With scanning electron microscopes that have resolutions better than 10 nm, spacings as small as 10 nm can be resolved.

It is desirable to reveal as much as possible of the surface details within all secondary cracks associated with fatigue-crack branching. This can best be achieved with the specimen oriented with the crack-propagation direction pointing toward the secondary-electron collector to gain maximum penetration of the primary electron beam into the depth of the secondary cracks.

The SEM fractographs in Fig. 18 and 19 show some of the characteristic features of fatigue-fracture surfaces.

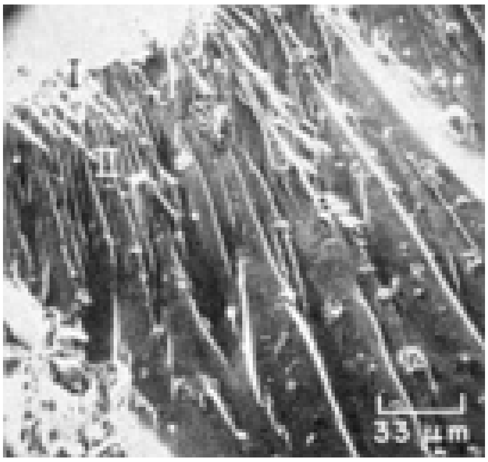


Fig. 18 Transition from stage I to stage II of a fatigue fracture in a coarse-grain specimen of aluminum alloy 2024-T3. The transition from stage I (upper left) to stage II is well defined. The presence of (Fe.Si)-rich inclusions did not affect the fracture path markedly. The inclusions, which were fractured, range from 5 to 25 μm (200 to 1000 μin.) in diameter. The stage II area shows a large number of approximately parallel fatigue patches containing very fine fatigue striations that are not resolved at this magnification.

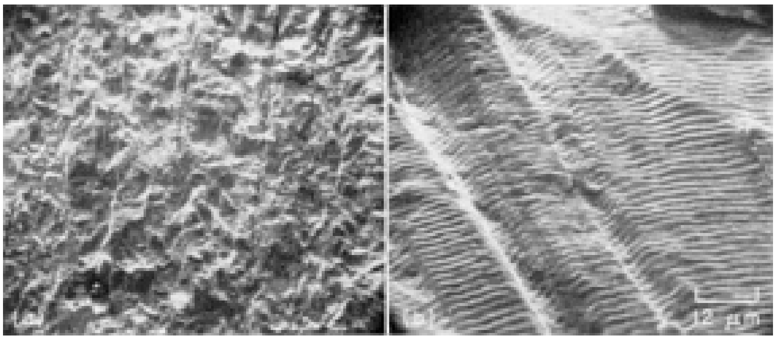


Fig. 19 Fatigue fracture in type 304 stainless steel tested at room temperature. The vertical secondary cracks in (a) are grain-boundary separations. The well-defined striations in (b) resulted from the planar slip characteristic of stainless steels.

Intergranular Fracture

Intergranular fracture (or decohesive rupture) is simply described as grain-boundary separation. It can occur by catastrophic brittle separation, or by separation plus microvoid coalescence on the interfaces of grains. Such fractures are regarded as the result of a severe reduction in grain-boundary energy by a Gibbsian (thermodynamic) adsorption mechanism. In its simplest form, segregation of metallic or gas-metal impurities can alter the grain-boundary free energy. Furthermore, grain-boundary energy can vary over a temperature range, leading to brittle-ductile fracture transitions and thermally induced brittle or ductile fractures. Variations in segregation at grain boundaries can also lead to mixed mechanisms of fracture, characterized by the appearance of dimpled areas in an intergranular fracture. Intergranular brittle fracture in the absence of an aggressive environment may be the result of segregation of a thermally activated impurity, which allows the grains to separate along smooth interfacial planes. Typical examples of fractures involving grain-boundary segregation are shown for tungsten, iridium, and a tungsten-rhenium alloy in Fig. 20.

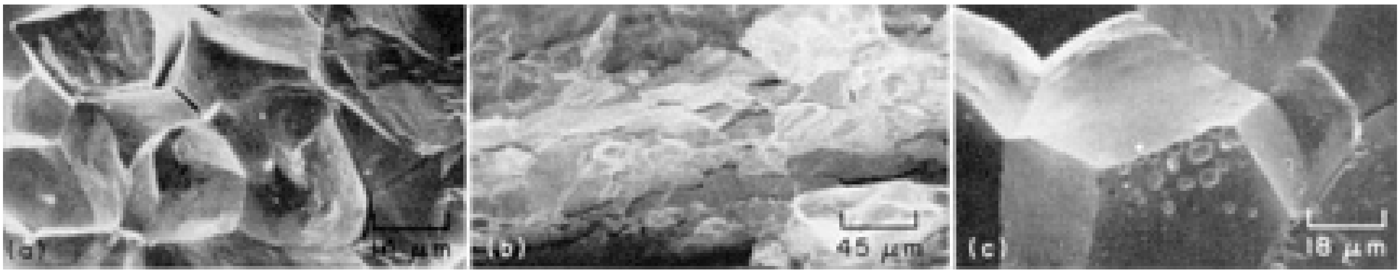


Fig. 20 Intergranular brittle fractures in tungsten, iridium, and a tungsten-3 wt% rhenium alloy. (a) Sintered tungsten rod drawn to 1.5 mm (0.060 in.) diam, recrystallized for 100 h at 10^{-6} torr and 2600 °C (4712 °F), and fractured in tension. (b) Iridium sheet annealed for 50 h in purified helium at 1700 °C (3092 °F) and broken by bending. (c) Tungsten-3 wt% rhenium alloy that was prepared in the same manner as the sintered tungsten rod in fractograph (a). Microvoids ("bubbles") at grain boundaries resulted from segregation of potassium (an impurity).

Features Indicative of Mixed Mechanisms of Fracture

A fracture that occurs by operation of two or more intermingled mechanisms of fracture is generally labeled a "mixed-mode" fracture. This is not to be confused with the successive operation of different fracture mechanisms, which can be analyzed sequentially and therefore require no special discussion. The occurrence of fracture by mixed mechanisms often indicates that the usual factors that determine the operative mechanism, such as state of stress, loading history, microstructure, and environment, favor both mechanisms; and that the local fracture mechanism is determined by a combination of deviations in these factors and the influence of secondary variables, such as local grain orientation.

The reasons for mixed mechanisms of fracture are as diverse as the fractures in which they have been observed. However, it is useful to identify the individual fracture mechanisms that contribute to such mixtures and to establish the circumstances that can lead to their individual occurrence. These circumstances establish limits. The occurrence of mixed mechanisms of fracture usually indicates that interacting influences have caused the fracture to depart from either limiting mechanism.

Mixed fracture mechanisms can result from quite different causes, and caution must be exercised in inferring the cause of fracture from the fracture features alone.

Features of Fractures Resulting from Chemical and Thermal Environments

For a specific metal or alloy, certain fracture mechanisms, such as cleavage, microvoid coalescence, fatigue, and intergranular separation, are often associated with particular environmental and stress states. The accumulation of experience with such fractures arising from known states of environment and stress makes it possible to ascertain, with the aid of fractography, the causes of fractures occurring under unknown service conditions. Some instances in which environment caused a specific fracture response that can be characterized through electron-microscope fractography are illustrated in Fig. 21 and 22.

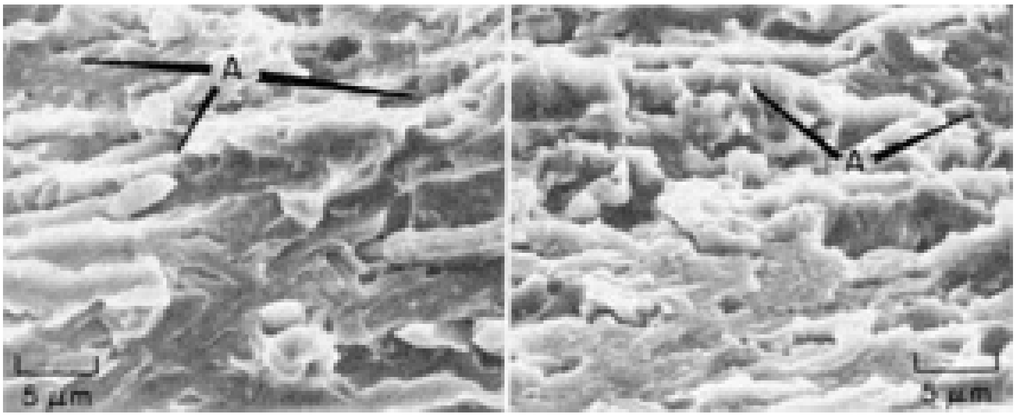


Fig. 21 Intermingled cleavage facets and dimples in two views of a stress-corrosion fracture in a step-cooled two-phase Ti-6Al-2Sn-4Zr-6Mo alloy exposed to a 3$\frac{1}{2}$% NaCl aqueous solution. Cleavage facets formed in the alpha phase, and poorly developed dimples, such as at the sites marked A, formed in the beta phase.

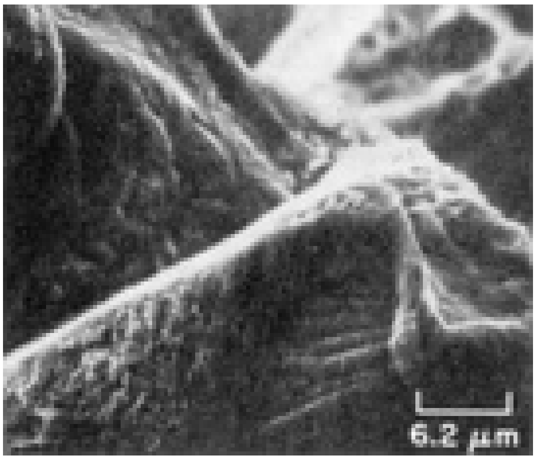


Fig. 22 Intergranular fracture in copper alloy C71500 (copper nickel, 30%) that became embrittled by grain-boundary oxidation during extended exposure to high-temperature steam in a heat exchanger. Crack penetration (which was cyclic, as intergranular layers of oxide formed, broke and reformed) produced fine striations that could be mistaken for fatigue striations.

Guide to Nondestructive Testing and Inspection Methods

Introduction

NONDESTRUCTIVE TESTING (NDT) and inspection techniques commonly used to detect and evaluate flaws (irregularities or discontinuities) or leaks in engineering systems are reviewed in this Section. Of the many different NDT techniques used in industry, liquid penetrant and magnetic particle testing account for about one-half of all NDT, ultrasonics and x-ray methods about another third, eddy current testing about 10%, and all other methods for only about 2% (Ref 1). It should be noted that the techniques reviewed in this Section are by no means all of the NDT techniques utilized. They do represent, however, the most commonly employed methods. Table 1 is a simplified breakdown of the complexity and relative requirements of the five most frequently used NDT techniques. Table 2 compares common NDT methods. Additional information on the various types of NDT methods can be obtained from the American Society for

Nondestructive Testing (Columbus, OH), *Nondestructive Testing,* Volume 03.03, published annually by ASTM (Philadelphia, PA), and in *Nondestructive Evaluation and Quality Control,* Volume 17, *ASM Handbook.*

Table 1 The relative uses and merits of various nondestructive testing methods

	Test method				
	Ultrasonics	**X-ray**	**Eddy current**	**Magnetic particle**	**Liquid penetrant**
Capital cost	Medium to high	High	Low to medium	Medium	Low
Consumable cost	Very low	High	Low	Medium	Medium
Time of results	Immediate	Delayed	Immediate	Short delay	Short delay
Effect of geometry	Important	Important	Important	Not too important	Not too important
Access problems	Important	Important	Important	Important	Important
Type of defect	Internal	Most	External	External	Surface breaking
Relative sensitivity	High	Medium	High	Low	Low
Formal record	Expensive	Standard	Expensive	Unusual	Unusual
Operator skill	High	High	Medium	Low	Low
Operator training	Important	Important	Important	Important	
Training needs	High	High	Medium	Low	Low
Portability of equipment	High	Low	High to medium	High to medium	High
Dependent on material composition	Very	Quite	Very	Magnetic only	Little
Ability to automate	Good	Fair	Good	Fair	Fair
Capabilities	Thickness gaging: some composition testing	Thickness gaging	Thickness gaging; grade sorting	Defects only	Defects only

Source: Ref 1

Table 2 Comparison of some nondestructive testing methods

Method	Characteristics detected	Advantages	Limitations	Example of use
Ultrasonics	Changes in acoustic impedance caused by cracks, nonbonds, inclusions, or interfaces	Can penetrate thick materials; excellent for crack detection; can be automated	Normally requires coupling to material either by contact to surface or immersion in a fluid such as water. Surface needs to be smooth.	Adhesive assemblies for bond integrity; laminations; hydrogen cracking
Radiography	Changes in density from voids, inclusions, material variations; placement of internal parts	Can be used to inspect wide range of materials and thicknesses; versatile; film provides record of inspection	Radiation safety requires precautions; expensive; detection of cracks can be difficult unless perpendicular to x-ray film.	Pipeline welds for penetration, inclusions, and voids; internal defects in castings
Visual optical	Surface characteristics such as finish, scratches, cracks, or color; strain in transparent materials; corrosion	Often convenient; can be automated	Can be applied only to surfaces, through surface openings, or to transparent material	Paper, wood, or metal for surface finish and uniformity
Eddy current	Changes in electrical conductivity caused by material variations, cracks, voids, or inclusions	Readily automated; moderate cost	Limited to electrically conducting materials; limited penetration depth	Heat exchanger tubes for wall thinning and cracks
Liquid penetrant	Surface openings due to cracks, porosity, seams, or folds	Inexpensive, easy to use, readily portable, sensitive to small surface flaws	Flaw must be open to surface. Not useful on porous materials or rough surfaces	Turbine blades for surface cracks or porosity; grinding cracks
Magnetic particles	Leakage magnetic flux caused by surface or near-surface cracks, voids, inclusions, or material or geometry changes	Inexpensive or moderate cost, sensitive both to surface and near- surface flaws	Limited to ferromagnetic material; surface preparation and post-inspection demagnetization may be required	Railroad wheels for cracks; large castings

Source: Ref 1

Reference

1. L. Cartz, Quality Control and NDT, *Nondestructive Testing,* ASM International, 1995, p 1-13

Important Definitions

The terms "nondestructive testing," or NDT, and "nondestructive inspection," or NDI, are considered synonymous. They both refer to a process or procedure, such as ultrasonic or radiographic inspection, for determining the quality or characteristics of a material, part, or assembly, without permanently altering the subject or its properties. All NDT or NDI methods are used to find internal anomalies (flaws) in a structure without degrading its properties or impairing its serviceability. The term "flaw" is a general term that is used to imply any irregularity, imperfection, or discontinuity contained in a material, part, or assembly. A flaw that has been evaluated as rejectionable is usually termed a "defect." The quantitative analysis of NDT/NDI findings to determine whether the material, part, or assembly will be acceptable for its function, despite the presence of flaws, is called "nondestructive evaluation," or NDE. With NDE, a flaw can be classified by its size, shape, type, and location, allowing the investigator to determine whether or not the flaw(s) is acceptable. Damage tolerant design approaches are based on the philosophy of ensuring safe operation in the presence of flaws (Ref 2, 3).

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Uses of NDT

Although flaw detection is usually considered the most important aspect of NDT, there are also other important application areas for these methods. These include leak detection, metrology, structure or microstructure characterization, stress/strain response determination, and rapid identification of metals and alloys. Each of these is briefly described in the following paragraphs; references to direct the reader to more detailed information are also supplied.

Leak Detection and Evaluation. Because many objects must withstand pressure, the nondestructive determination of leakage is extremely important. The NDT area known as leak detection utilizes many techniques, as described in the article "Leak Testing" in this Section. Each technique has a specific range of applications, and a particular leak detection technique should be selected only after careful consideration.

Metrology. The measurement of dimensions, referred to as "metrology," is one of the most widely used NDT activities, although it is not considered with other conventional NDT activities, such as flaw detection. In recent years, conventional tools for metrology, such as micrometer calipers, vernier calipers, and dial gages, have been supplemented with modern high-technology metrology tools, such as laser inspection, coordinate measuring machines, and machine vision and robotic inspection systems (Ref 4, 5, 6).

The selection of a metrology system is highly dependent on the specific requirements of a given application. Standard reference works on the topic should be consulted for conventional metrology. In addition, other NDE methods, such as eddy current, ultrasonic, optical holography, and speckle metrology, often find application in the field of metrology.

Structure or Microstructure Characterization. Another interesting area of NDT is microstructural characterization, which can be done in situ without damaging the object by using replication microscopy. This is widely used to assess the condition of power plant and petrochemical metallic components on a large scale (Ref 7), or by using conventional optical microscopy techniques with portable equipment, including polishing, etching, and microscopic equipment. In addition, it is possible to characterize the microstructure through the correlation with some type of NDT information. For example, the transmission of ultrasonic energy has been correlated with the microstructure of gray cast iron.

Microstructure can often be characterized by determining physical or mechanical properties with NDT techniques because there is usually a correlation among microstructure, properties, and NDT response. Characterizing microstructure from NDT responses is a relatively recent area of NDT application, and new developments are occurring frequently.

Stress/Strain and Dynamic Response Determination. The local strain at a specific location in an object under a specific set of loading conditions can be determined by using strain sensing methods such as photoelastic coatings, brittle coatings, or strain gages (Ref 8). If the stress-strain behavior of the material is known, these strain values can be converted into stress values.

Residual stresses in materials can be nondestructively measured by a variety of methods, including x-ray diffraction (Ref 9), ultrasonics (Ref 10), and electromagnetics (Ref 11, 12). With the x-ray diffraction technique, the interatomic planar distance is measured, and the corresponding stress is calculated. The penetration depth of x-rays is of the order of only 10 μm (400 μin.) in metals. Therefore, the technique is limited to measurements of surface stresses. Its use has been generally limited to the laboratory because of the lack of field-usable equipment and concern with radiation safety.

With ultrasonic techniques, the velocity of the ultrasonic waves in materials is measured and related to stress. These techniques rely on a small velocity change caused by the presence of stress, which is known as the acoustoelastic effect. In principle, ultrasonic techniques can be used to measure bulk as well as surface stresses. Because of the difficulty in differentiating stress effects from the effect of material texture, practical ultrasonic applications have not yet materialized.

With electromagnetic techniques, one or more of the magnetic properties of a material (such as permeability, magnetostriction, hysteresis, coercive force, or magnetic domain wall motion during magnetization) are sensed and correlated to stress. These techniques rely on the change in magnetic properties of the material caused by stress; this is known as the magnetoelastic effect. These techniques, therefore, apply only to ferromagnetic materials, such as steel.

Rapid Identification of Metals and Alloys. Quality assurance during the fabrication of hardware, subassemblies, and assemblies sometimes requires a reliable system of rapid identification of metals and alloys. Because various metals may become mixed during storage or use, and because lengths of strip, sheet, plate, billets, bars, wire, and fabricated products may have lost their identifying marks, some means of sorting mixed lots is necessary. The best method of identifying such items is by quantitative chemical analysis. However, chemical or spectrographic analyses require extensive, time-consuming procedures and expensive equipment that may not be fully utilized. Also, a complete chemical analysis often may be unnecessary.

Common methods of rapid identification of metals include techniques involving the magnetic properties and weight of the metal, spark testing (of ferrous alloys), and chemical spot testing. Each of these methods is discussed in Ref 13. Spark testing is also described in the Section "Recycling and Life-Cycle Analysis" in this Handbook.

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Leak Testing

Introduction

LEAK TESTING is used to determine the rate at which a liquid or gas penetrates from inside a "tight" component or assembly to the outside, or vice versa. Penetration occurs as a result of a pressure differential between the two regions, or of permeation of a somewhat extended barrier. The term "leak" commonly refers to an actual discontinuity or passage through which a fluid flows or permeates.

Types of Leaks. Two basic types of leaks are real leaks and virtual leaks. A real leak essentially is a localized leak; that is, a discrete passage through which fluid can flow (crudely, a hole). Such a leak can take the form of a tube, a crack, an orifice, and so on. A system also can leak through permeation of a somewhat extended barrier; this type of real leak is called a distributed leak. A gas can flow through a solid having no holes large enough to permit more than a small fraction of the gas to flow through any one hole. This process involves diffusion through the solid and also can involve various surface phenomena such as absorption, dissociation, migration, and desorption of gas molecules. Virtual leaks are leaks that involve the gradual desorption of gases from surfaces and components within a vacuum system. It is not uncommon for a vacuum system to have both real leaks and virtual leaks at the same time.

Leak Testing of Fluid Systems at Pressure

Leak-testing methods are classified according to the pressure and fluid (gas or liquid) in the system. Table 1 lists the common fluid-system leak-testing methods and the methods used in leak testing of vacuum systems.

Table 1 Pressure and vacuum system leak-testing methods

Gas systems at pressure

- Direct sensing by:
    - Acoustic methods
    - Bubble testing
    - Flow detection
- Gas detection by:
    - Smell
    - Chemical reaction
    - Halogen gas
    - Sulfur hexafluoride
    - Combustible gas
    - Thermal-conductivity gages

    - Infrared gas analyzers
    - Mass spectrometry
    - Radioisotope count
    - Ionization gages
    - Gas chromatography

- Quantity-loss determination by:

    - Weighing
    - Gaging differential pressure

Liquid systems at pressure

- Unaided visual methods
- Aided visual methods
- Surface wetting
- Weight loss
- Water-soluble paper with aluminum foil

Vacuum systems

- Manometers
- Halogen gas
- Mass spectrometry
- Ionization gages
- Thermal-conductivity gages
- Gas chromatography

Leak detection by monitoring changes in pressure of the internal fluid often is used when leak-detection equipment is not immediately available. Generally, detection can be accomplished using instruments that are already installed in the system.

Acoustic Methods

Turbulent flow of a pressurized gas through a leak produces sound of both sonic and ultrasonic frequencies. If the leak is large, it probably can be detected with the ear. This is an economical and fast method to find gross leaks. Sonic emissions also are detected using such instruments as stethoscopes and microphones that have a limited ability to locate and determine the approximate size of a leak. Electronic transducers enhance detection sensitivity.

Bubble Testing

A simple method used to leak test small vessels pressurized with any gas is to submerge them in a liquid and observe for bubbles. If the test vessel is sealed at atmospheric pressure, a pressure differential can be obtained by pumping a partial vacuum over the liquid and by heating the liquid. The sensitivity of this test is increased by reducing (a) the pressure above the liquid, (b) the liquid density, (c) the depth of immersion in the liquid, and (d) the surface tension of the liquid.

Specific-Gas Detectors

Many available types of leak detectors react to either a specific gas or a group of gases that have some specific physical and/or chemical property in common.

Sulfur hexafluoride detectors operate on the principle of electron-capture detectors, used widely in the field of gas chromatography. The sensing chamber of a sulfur hexafluoride detector consists of a cylindrical cell, which has a centrally mounted insulated probe. The inner wall of the cell is coated with a radioactive element (300 millicuries of tritium). Low-energy electrons emitted by the tritium are collected on the central probe by means of a polarizing voltage maintained between the probe and the cell wall. The resulting electric current is amplified and displayed on a conventional meter. The display meter is a taut band-suspension microammeter reading 0 to 50, and response time of the instruments one second. Leak-rate sensitivity is 10^{-8} mL/s.

Mass-Spectrometer Testing. A mass spectrometer basically is a device to sort charged particles. The sample gas enters the analyzer where its molecules are bombarded by a stream of electrons emitted by a filament. The bombarded molecules lose an electron and become positively charged ions, which are electrostatically accelerated to a high velocity. Because the analyzer lies in a magnetic field perpendicular to the ion path, the ions travel distinct, curved paths according to their mass. The radii of these paths are determined by ion mass, the magnitude of initial acceleration, and the strength of the magnetic field. With a constant magnetic field, any group of ions having the same mass can be made to travel the specific radius necessary to strike the ion collector. The positive charge of the ion is imparted to the target, or collector, and the resulting current flow is proportional to the quantity of the ions of that particular mass.

Application of Specific-Gas Detectors

The proper method for using a specific-gas detector is based on the function of the leak detector, the fluid that is leaking, and the type of vessel being tested. One of the best methods of using a leak detector is discussed below.

Probing. Probes, which will react to a number of gases, can be used in either of two ways: the probe mode and the monitoring of an enclosure placed around the pressurized item.

In the probe mode, the external surface of the pressurized vessel is scanned either with a portable detector having a short probe attached, or with a long probe connected to a stationary leak detector by flexible tubing (Fig. 1). In general, the connection of a long probe to a stationary detector reduces sensitivity because of the slow release of absorbed gases in the probe tubing, which results in a high background reading. Because a correspondingly longer time is required for the gas to flow up the tube to the sensing element, it is difficult to pinpoint the location of the leak.

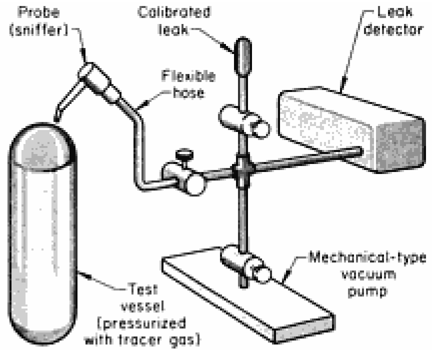

Probe (sniffer)
Calibrated leak
Leak detector
Flexible hose
Mechanical-type vacuum pump
Test vessel (pressurized with tracer gas)

Fig. 1 Schematic showing connection of a long probe by a flexible hose to a stationary leak detector to scan the external surface of a pressurized vessel

In the monitoring of an enclosure placed around the pressurized item, the item is enclosed in a plastic bag and the accumulation of tracer gas in the bag is monitored by a leak detector connected to the bag by a short probe.

Back pressuring is a method of pressurized testing that typically is used with small, hermetically sealed electronic components such as integrated circuits, relays, and transistors. In this method, the test unit is placed in a pressurized container filled with a tracer gas and is kept there for a time to allow tracer gas to flow into the unit through any leaks that exist.

In using back pressuring, care must be taken to ensure that the leaking components contain tracer gas. Therefore, it is important that the time between back pressuring and leak testing be suitably controlled. For example, in a test specification for transistors, the transistors were subjected to helium pressure of 100 psi for 16 h, air washed for 4 min, and then leak tested within 3 h. If more than 3 h elapsed before leak testing, the transistors were pressurized again.

Because leaks generally are expected to be quite small, very sensitive tracer-detector combinations must be used. The tracer gas typically used is helium or krypton 85, and detection is by use of a helium mass spectrometer or a nuclear-radiation detector, respectively. Absolute values of the size of the leak sometimes are difficult to determine with back pressuring, because of (a) adsorption and absorption of the tracer gases and (b) different detector-response times for different leak directions.

Visual Inspection

Introduction

VISUAL INSPECTION is a nondestructive testing technique that provides a means to detect and examine a variety of surface flaws, such as corrosion, contamination, surface finish, and surface discontinuities. Visual inspection is the most widely used method for detecting and examining surface cracks.

Visual inspection methods range from examination with the naked eye to the use of interference microscopes to measure the depth of scratches in the finish of finely polished and lapped surfaces. Equipment used to aid visual inspection includes:

- Flexible and rigid borescopes to illuminate and observe internal, closed, and otherwise inaccessible areas
- Image sensors for remote sensing and to develop permanent visual records in the form of photographs, videotapes, and computer-enhanced images
- Magnifying systems to evaluate surface finish, surface shapes (profile and contour gaging), and surface microstructures
- Dye and fluorescent penetrants and magnetic particles to enhance the observation of surface cracks (and sometimes near-surface conditions in the case of magnetic-particle inspection)

Borescopes

A borescope (Fig. 1) is a long, tubular optical device that illuminates and allows the inspection of surfaces inside narrow tubes and difficult-to-reach chambers. The tube, which can be rigid or flexible with a wide variety of lengths and diameters, provides the necessary optical connection between the viewing end and an objective lens at the distant, or distal, tip of the borescope. Three ways to achieve the optical connection are:

- A rigid tube with a series of relay lenses
- A tube (normally flexible, but also rigid) with a bundle of optical fibers
- A tube (normally flexible) with wiring that carries the image signal from a charge-coupled device (CCD) imaging sensor at the distal tip

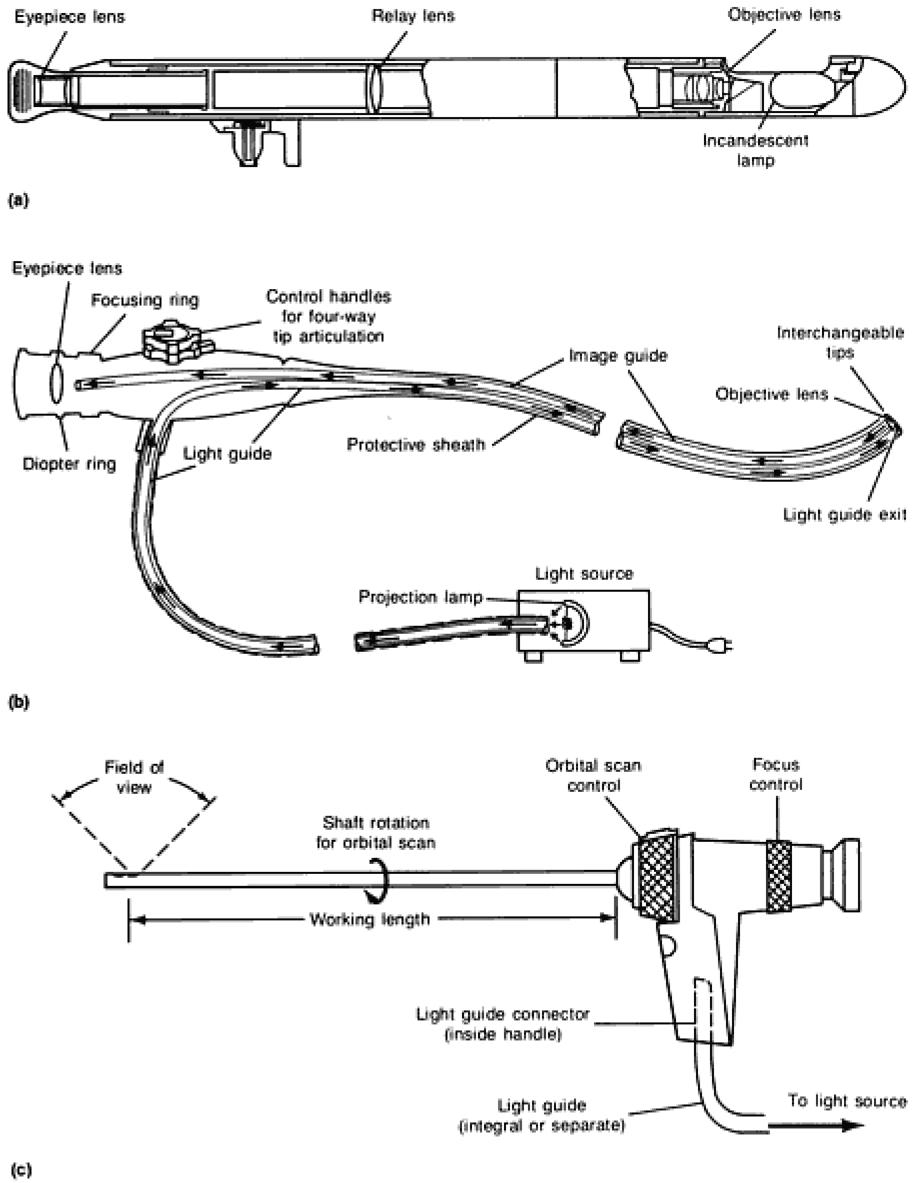

Eyepiece lens
Relay lens
Objective lens
Incandescent lamp
(a)
Eyepiece lens
Focusing ring
Control handles for four-way tip articulation
Image guide
Interchangeable tips
Objective lens
Diopter ring
Light guide
Protective sheath
Light guide exit
Light source
Projection lamp
(b)
Field of view
Orbital scan control
Focus control
Shaft rotation for orbital scan
Working length
Light guide connector (inside handle)
Light guide (integral or separate)
To light source
(c)

Fig. 1 Three typical designs of borescopes. (a) Rigid borescope with a lamp at the distal end. (b) Flexible fiberscope with a light source. (c) Rigid borescope with a light guide bundle in the shaft.

These three basic tube designs can have either fixed or adjustable focusing of the objective lens at the distal tip. The distal tip also has prisms and mirrors that define the direction and field of view (see Fig. 2). Generally, a fiber optic light guide and a lamp producing white light is used in the illumination system, although ultraviolet light can be used to inspect surfaces treated with liquid fluorescent penetrants. Light-emitting diodes at the distal tip are sometimes used for illumination in videoscopes with working lengths greater than 15 m (50 ft).

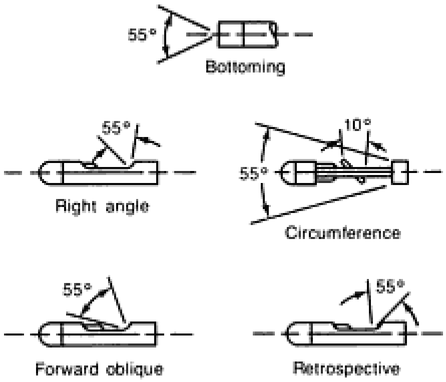


Fig. 2 Typical directions and field of view with rigid borescopes

Rigid Borescopes

Rigid borescopes generally are limited to use in applications with a straight-line path between the observer and the area to be observed. The sizes range from 0.15 to 30 m (0.5 to 100 ft) long and 0.9 to 70 mm (0.035 to 2.75 in.) in diameter. Magnification usually is 3 to 4×, but magnifying power up to 50× is available. The illumination system is either an incandescent lamp located at the distal end (Fig. 1a) or a light guide bundle made of optical fibers (Fig. 1c), which conduct light from an external source.

Rigid borescopes typically have a series of achromatic relay lenses in the optical tube. The borescopes generally have a 55° field of view, although the field of view can range from 10 to 90°. Some rigid borescopes have orbital scan (Fig. 1c), which involves the rotation of the optical shaft for scanning purposes. The amount of rotation can vary from 120 to 370°. Some rigid borescopes also have movable prisms at the tip for scanning. The illumination system can be either a distal lamp or a light guide bundle, and the various features may include orbital scan, various viewing heads, and adjustable focusing of the objective lens.

Miniborescopes. Instead of conventional relay lenses, miniborescopes have either a single image-relaying rod or quartz fiber in the optical tube. Miniborescopes are 110 and 170 mm (4.3 and 6.7 in.) long, and range from 0.9 to 2.7 mm (0.035 to 0.105 in.) in diameter. High magnification (up to 30×) can be achieved at minimal focal lengths, and an adjustable focus is not required because the scope has an infinite depth of field. Miniborescopes use an integral light guide bundle.

Hybrid borescopes use rod lenses combined with convex lenses to relay the image. A larger light guide bundle is used, which provides higher illumination and a larger image with a higher degree of contrast.

Hybrid borescopes are up to 990 mm (39 in.) long, and 5.5 to 12 mm (0.216 to 0.47 in.) in diameter. All hybrid borescopes have adjustable focusing of the objective lens and a 370° rotation for orbital scan.

Extendable borescopes allow the user to construct a longer borescopic tube by joining extension tubes. The borescopes are available with either a fiber-optic light guide or an incandescent lamp at the distal end. Extendable borescopes with an integral lamp have a maximum length of approximately 30 m (100 ft). Maximum length of scopes with a light guide bundle is about 8 m (26 ft), which allows smaller tube diameters (as small as 8 mm, or 0.3 in.). Interchangeable viewing heads are also available. Extendable borescopes do not have adjustable focusing of the objective lens.

Rigid chamberscopes allow more rapid inspection of larger chambers. Chamberscopes have variable magnification (zoom), a lamp at the distal tip, and a scanning mirror, which allows the user to observe in different directions. The higher illumination and greater magnification of chamberscopes allow the inspection of surfaces as far as 910 mm (36 in.) away from the distal tip of the scope.

Mirror sheaths convert a direct-viewing borescope into a side-viewing scope. A mirror sheath is designed to fit over the tip of the scope, and, therefore, reflects an image from the side of the scope. Side, forward-oblique, and retrospective viewing heads provide better resolution and a higher degree of image contrast. A mirror sheath also produces an inverse image and can produce unwanted reflections from the shaft.

Scanning. In addition to the orbital scan feature described previously, some rigid borescopes have the ability to scan longitudinally along the axis of the shaft. This is accomplished using a movable prism with a control at the handle. Typically, the prism can shift the direction of view through an arc of 120°.

Flexible Borescopes

Flexible borescopes are used primarily in applications that do not have a straight passageway to the point of observation. Two types of flexible borescopes are flexible fiberscopes and videoscopes with a CCD image sensor at the distal tip.

Flexible Fiberscopes. A typical fiberscope (Fig. 1b) consists of a light guide bundle, an image guide bundle, an objective lens, interchangeable viewing heads, and remote controls for articulation of the distal tip. Fiberscopes are available in diameters from 1.4 to 13 mm (0.055 to 0.5 in.) and ranging up to 12 m (40 ft) long. Special quartz fiberscopes are available in lengths up to 90 m (300 ft).

Fibers in the image guide must be precisely aligned so they are in an identical relative position to each other at their terminations for proper image resolution. Fiber diameter also is a factor in obtaining good image resolution. With smaller diameter fibers, a brighter image with better resolution can be obtained because more fibers can be packed in the image guide. Higher resolution makes it possible to use an objective lens with a wider field of view and also to magnify the image at the eyepiece. This allows better viewing of objects at the periphery of the image.

The interchangeable distal tips provide various directions and fields of view on a single fiberscope. However, because the tip can be articulated for scanning purposes, distal tips with either a forward or side viewing direction usually are sufficient. Fields of view are typically 40 to 60°, although they can range from 10 to 120°. Most fiberscopes provide adjustable focusing of the objective lens.

Videoscopes with CCD probes involve the electronic transmission of color or black and white images to a video monitor. The distal end of electronic videoscopes contains a CCD chip. The objective lens focuses the image of an object on the surface of the CCD chip, converting light to electrons, which are stored in each picture element, or pixel, of the CCD device. Thus, the image of the object is stored on the CCD device.

Videoscopes with CCD probes produce images having spatial resolutions of the order of those described in Fig. 3. Resolution depends on the object-to-lens distance and the fields of view, factors that affect the degree of magnification. Generally, videoscopes produce higher resolution than fiberscopes.

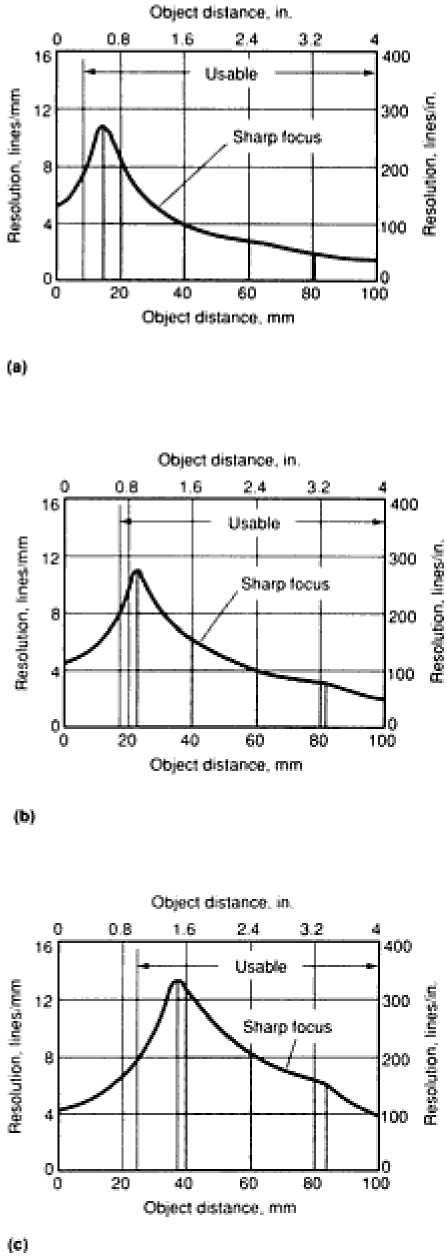


Fig. 3 Typical resolution of charge-coupled device videoscopes with a (a) 90° field of view, (b) 60° field of view, and (c) 30° field of view

Another advantage of videoscopes is their longer working length. With a given amount of illumination at the distal tip, videoscopes can return an image over a greater length than fiberscopes. Videoscopes help reduce eye fatigue. Also, there is no honeycomb pattern or irregular picture distortion as with some fiberscopes, the electronic form of the image signal allows digital image enhancement and the potential for integration with automatic inspection systems, and the display allows the generation of reticles on the viewing screen for point-to-point measurements.

Special Features

Measuring borescopes and fiberscopes contain a movable cursor that allows measurements during viewing. When the object under measurement is in focus, the movable cursor provides a reference for dimensional measurements in the optical plane of the object. This capability eliminates the need to know the object-to-lens distance when determining magnification factors.

Working channels are used in borescopes and fiberscopes to pass working devices, such as measuring instruments, retrieval devices, and hooks to help insert thin, flexible fiberscopes, to the distal tip.

Selection

Factors that influence the choice of a flexible or rigid borescope for use in a specific application include focusing, illumination, magnification, working length, direction of view, and environment.

Focusing and Resolution. In general, the optical quality of a rigid borescope improves as the size of the lens increases. Therefore, a borescope with the largest possible diameter should be used. For fiberscopes, the resolution is dependent on the alignment accuracy and fiber diameter in the image bundle. Smaller-diameter fibers provide more resolution and edge contrast when combined with good geometrical alignment of the fibers.

Illumination. The required intensity of the light source is determined by the reflectivity of the surface, the area of surface to be illuminated, and the transmission losses over the length of the scope. At working lengths greater than 6 m (20 ft), rigid borescopes with a lamp at the distal end provide the greatest amount of illumination over the widest area. Fiber-optic illumination in scopes with working lengths less than 6 m (20 ft) is always brighter and is suitable for heat-sensitive applications because filters can remove infrared frequencies.

Magnification and field of view are interrelated; field of view decreases as magnification increases. The precise relationship between magnification and field of view is specified by the manufacturer.

The degree of magnification in a particular application is determined by the field of view and the distance from the objective lens to the object. The magnification increases when either the field of view or the lens-to-object distance decreases.

Working length can sometimes dictate the use of a particular type of scope. For example, a rigid borescope with a long working length might be limited by the need for additional supports. In general, videoscopes allow a longer working length than fiberscopes.

Direction of View. Flexible fiberscopes and videoscopes, because of their articulating tip, are often adequate with either a side or forward viewing tip.

Circumferential and panoramic heads are designed to inspect tubing and other cylindrical structures. A centrally located mirror permits right-angle viewing of an area just scanned by the panoramic view.

The forward viewing head permits the inspection of the area directly ahead of the viewing head. It is commonly used when examining facing walls or the bottoms of blind holes and cavities.

Forward-oblique heads bend the viewing direction at an angle to the borescope axis, permitting the inspection of corners at the end of a bored hole. The retrospective viewing head bends the cone of view at a retrospective angle to the borescope axis, providing a view of the area just passed by the advancing borescope. It is especially suited to inspecting the inside neck of cylinders and bottles.

Environment. Flexible and rigid borescopes can be manufactured to withstand a variety of environments. Although most flexible and rigid borescopes can operate at temperatures ranging from -34 to 66 °C (-30 to 150 °F), specially designed scopes can be used at temperatures to 1925 °C (3500 °F). Scopes can also be manufactured for use in liquid media.

Special scopes are required for use at pressures above ambient and in atmospheres exposed to radiation. Scopes used in a gaseous environment should be made explosion proof.

Applications

The principal use of borescopes is in equipment maintenance programs, where they can help reduce or eliminate the need for costly teardowns. Some types of equipment, such as turbines, have access ports that are specifically designed for borescopes. Borescopes provide a means to check in-service defects in various equipment, such as automotive components (Fig. 4), turbines, and process piping.

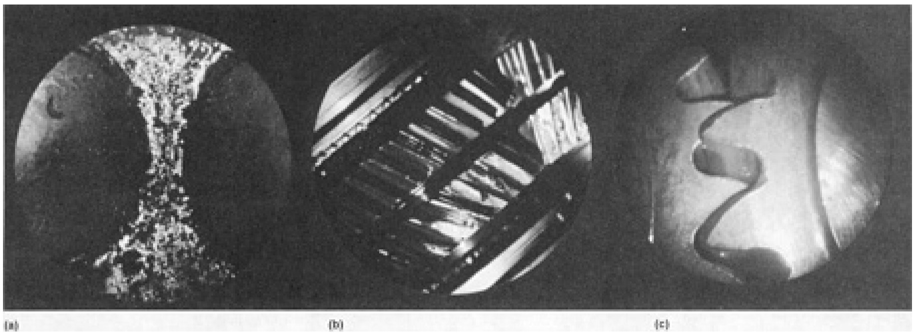


Fig. 4 In-service defects as seen through a borescope designed for automotive servicing. (a) Carbon on valves. (b) Broken transmission gear tooth. (c) Differential gear wear.

Optical Sensors

Visible light, which can be detected by the human eye and with optical sensors, has some advantages over inspection methods based on nuclear, microwave, and ultrasound radiation. For example, one of the advantages of visible light is the capability of tightly focusing the probing beam on the inspected surface. High spatial resolution can result from this sharp focusing, which is useful in gaging and profiling applications.

Different types of image sensors used in visual inspection include:

- Vidicon or plumbicon television tubes
- Secondary electron-coupled (SEC) vidicons
- Image orthicons and image isocons
- Charge-coupled device sensors
- Holographic plates (see the article "Holography" in this Section)

Television cameras with vidicon tubes are useful at higher light levels (approximately 0.2 lm/m^2, or 10^{-2} ftc), while orthicons, isocons, and SEC vidicons are useful at lower light levels.

Charge-coupled devices are suitable for use in many different information-processing applications, including image sensing in television-camera technology. Charge-coupled devices offer an advantage over vacuum-tube image sensors because of the reliability of their solid-state technology, their operation at low voltage and low power dissipation, extensive dynamic range, visible and near-infrared response, and geometric reproducibility of image location. Image enhancement (or visual feedback into robotic systems) typically involves the use of CCDs as the optical sensor or the use of television signals that are converted into digital form.

Optical sensors are also used in inspection applications that do not involve imaging. However, in some applications, incoherent light sources are very effective in nonimaging inspection applications using optical sensors.

Magnifying Systems

Magnifying systems are used in visual reference gaging. When tolerances are too tight to judge by eye alone, optical comparators or toolmakers' microscopes are used to achieve magnifications ranging from 5 to 500×.

A toolmakers' microscope consists of a microscope mounted on a base that carries an adjustable stage, a stage transport mechanism, and supplementary lighting. Various objective lenses provide magnifications ranging from 10 to 200×.

Optical comparators are magnifying devices that project the silhouette of small parts onto a large projection screen. The magnified silhouette is then compared against an optical comparator chart, which is a magnified outline drawing of the workpiece being gaged. Optical comparators are available with magnifications ranging from 5 to 500×.

Parts with recessed contours can also be successfully gaged on optical comparators using a pantograph. One arm of the pantograph is a stylus that traces the recessed contour of the part, and the other arm carries a follower that is visible in the light path. As the stylus moves, the follower projects a contour on the screen.

Liquid-Penetrant Inspection

Introduction

LIQUID-PENETRANT INSPECTION is a nondestructive method used to find discontinuities that are open to the surface of solid, essentially nonporous materials. Indications of flaws can be found regardless of the size, configuration, internal structure, and chemical composition of the workpiece being inspected, as well as flaw orientation. Liquid penetrants can seep into (and be drawn into) various types of minute surface openings (as fine as 0.1 μm, or 4 μin., in width) by capillary action. Therefore, the process is well suited to detect all types of surface cracks, laps, porosity, shrinkage areas, laminations, and similar discontinuities. It is used extensively to inspect ferrous and nonferrous metal wrought and cast products, powder metallurgy parts, ceramics, plastics, and glass objects.

The liquid-penetrant inspection method is relatively simple to perform, there are few limitations due to specimen material and geometry, and it is inexpensive. The equipment is very simple, and the inspection can be performed at many stages in the production of the part, as well as after the part is placed in service. Relatively little specialized training is required to perform the inspection. In some instances, liquid-penetrant sensitivity is greater for ferromagnetic steels than that of magnetic-particle inspection.

The major limitation of liquid-penetrant inspection is that it can detect only imperfections that are open to the surface; some other method must be used to detect subsurface defects and discontinuities. Another factor that can inhibit the effectiveness of liquid-penetrant inspection is the surface roughness of the object. Extremely rough and porous surfaces are likely to produce false indications.

Although the liquid-penetrant method often is used to inspect some types of powder metallurgy parts, the process generally is not well suited to inspect low-density powder metallurgy parts and other porous materials because the penetrant enters the pores and registers each pore as a defect.

Physical Principles

Liquid-penetrant inspection depends mainly on the ability of liquid penetrant to effectively wet the surface of a solid workpiece or specimen; flow over the surface to form a continuous, reasonably uniform coating; and migrate into cavities that are open to the surface. The cavities of interest usually are very small, often invisible to the unaided eye. The ability of a given liquid to flow over a surface and enter surface cavities depends principally on:

- Cleanness of the surface
- Configuration of the cavity
- Size of the cavity
- Surface tension of the liquid
- Ability of the liquid to wet the surface

The cohesive forces between molecules of a liquid cause surface tension. An example of the influence of surface tension is the tendency of free liquid, such as a droplet of water, to contract into a sphere. In such a droplet, surface tension is counterbalanced by the internal hydrostatic pressure of the liquid. When the liquid comes into contact with a solid surface, the cohesive force responsible for surface tension competes with the adhesive force between the molecules of the liquid and the solid surface. These forces jointly determine the contact angle between the liquid and the surface. If the angle is less than 90°, the liquid has good wetting ability.

Description of the Process

Regardless of the type of penetrant used and other variations in the basic process, liquid-penetrant inspection requires at least five essential steps:

Surface Preparation. All surfaces of a work-piece must be thoroughly cleaned and completely dried before inspection. Discontinuities exposed to the surface must be free from oil, water, and other contaminants for at least 25 mm (1 in.) beyond the area being inspected to increase the probability of detection.

Penetrant Application. Liquid penetrant is applied in a suitable manner to form a film of the penetrant over the surface for at least 13 mm ($\frac{1}{2}$ in.) beyond the area being inspected. The penetrant is left on the surface for a sufficient time to allow penetration into flaws. Times are based on experience. Table 1 shows some typical times for different materials and defect types.

Table 1 Typical penetration time for a dye penetrant

Surface under examination	Type of defect	Penetration time, min
All	Heat-treatment cracks	2
	Grinding	10
	Cracks	10
Ceramics	Cracks	2-5
	Porosity	2-5
Aluminum welds	Cracks and pores	10-20
Steel welds	Cracks and pores	10-20
Forgings	Cracks	20
	Laps	20
Metal rollings	Seams	10-20
Die castings	Surface porosity	3-10
	Cold shuts	10-20
Metal-permanent mold casting	Shrinkage porosity	3-10
Carbide-tipped cutting tools	Poor braze	2-10
Cutting tools	Cracks in steel	2-10
	Cracks in tip	2-10

Removal of Excess Penetrant. Uniform removal of excess penetrant is necessary for effective inspection, but overcleaning must be avoided. Penetrants can be washed off directly using water, treated first with an emulsifier and then rinsed with water, or removed using a solvent.

Developer Application. Developer can be applied by dusting (dry powdered) and immersion and spray (water developers) applications. Nonaqueous wet developers can only be applied by spraying. The developer should be allowed to dwell on the surface for a sufficient time (usually 10 min minimum) to permit it to draw penetrant out of any surface flaws to form visible indications of such flaws. Longer times could be necessary for tight cracks. The developer also provides a uniform background to assist visual inspection.

Inspection. After being sufficiently developed, the surface is visually examined for indications of penetrant bleedback from surface openings. This examination must be performed in a suitable inspection environment. Visible-penetrant inspection is performed in good white light. When fluorescent penetrant is used, inspection is performed in a suitably darkened area using black (ultraviolet) light, which causes the penetrant to emit visible light. The actions of penetrant and developer are shown in Fig. 1.

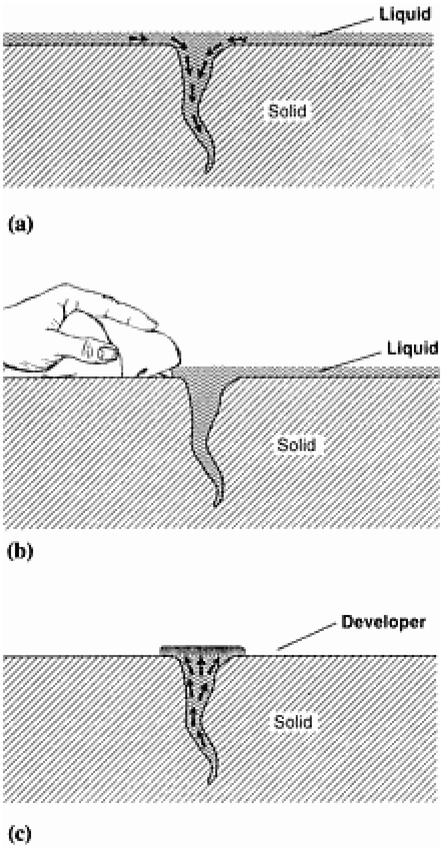


Fig. 1 Actions of penetrant and developer. (a) Penetrant liquid is drawn into an open crack by capillary action. (b) Excess surface penetrant is removed by wiping with a cloth, washing directly with water, treating with an emulsifier and rinsing, or removing with a solvent. (c) Developer applied to the surface draws out penetrant liquid that seeps into the developer forming a visible indication of the surface crack. A colored dye or a fluorescence compound is usually added to the penetrant liquid. Depending on the amount of penetrant that seeps into the developer, the crack width can appear 100 times larger than its actual size.

Penetrant Systems

Liquid penetrant inspection applications have been developed to handle the wide variations in three basic penetrant systems. They are broadly classified as (a) the water-washable system, (b) the postemulsifiable system, and (c) the solvent-removable system.

The water-washable penetrant system is designed so that the penetrant is directly washable from the surface of the workpiece using water. It can be used to process workpieces quickly and efficiently. However, it is important that washing is carefully controlled, because water-washable penetrants are susceptible to overwashing. The degree and speed of removal depend on processing conditions such as spray-nozzle characteristics, water pressure and temperature, duration of rinse cycle, surface condition of the workpiece, and inherent removal characteristics of the penetrant employed.

The Postemulsifiable System. High-sensitivity penetrants that are not water washable are used to ensure detection of minute discoveries in some materials. Because they are not water washable, the danger of washing the penetrant out of the flaws is reduced. These penetrants require an additional operation in the inspection process. An emulsifier must be applied after the application of penetrant and proper penetration (dwell) time. The emulsifier makes the penetrant soluble in water so the excess penetrant can be removed by water rinsing. Therefore, the emulsification time must be carefully controlled so the surface penetrant becomes water-soluble but penetrant in the flaws does not. Postemulsifiable penetrants include lipophilic (oil base) and hydrophilic (water base).

The Solvent-Removable System. Occasionally, it is necessary to inspect only a small area of a workpiece or to inspect a workpiece on site rather than at a regular inspection station. In such situations, solvent-removable penetrants are used. Normally, the same type of solvent is used both for precleaning and for removal of excess penetrant. This penetrant process is convenient and broadens the range of applications of penetrant inspection.

The solvent-removable penetrants have an oil base. Optimum solvent removal is accomplished by wiping off as much of the excess penetrant as possible with a paper towel or a lint-free cloth, then slightly dampening a clean cloth with solvent and wiping off the remaining penetrant. Final wiping with a dry paper towel or clean cloth is required.

The penetrant also can be removed by flooding the surface with solvent, in the same manner as for water-washable penetrants. The flooding technique is particularly useful for large workpieces, but it must be very carefully used to prevent removal of the penetrant from the flaws.

The solvent-removable system is used mainly in special applications; it is not practical for production applications because it is labor intensive.

Liquid-Penetrant Materials

Two basic types of liquid penetrants are fluorescent and visible. Each type is available for any one of the three systems (water-washable, postemulsifiable, or solvent-removable).

Fluorescent-penetrant inspection uses penetrants that fluoresce brilliantly under ultraviolet light. The sensitivity of a fluorescent penetrant depends on its ability to form indications that appear as small sources of light in an otherwise dark area. Sensitivity levels of fluorescent penetrants are: ultralow (Level $\frac{1}{2}$), low (Level 1), medium (Level 3), high (Level 4), and ultrahigh (Level 5).

Visible penetrant inspection uses a penetrant that is usually red in color and produces vivid red indications in contrast to the light background of the applied developer under visible light. The visible penetrant indications must be viewed under adequate white light. The sensitivity of visible penetrants is regarded as Level 1 and adequate for many applications.

Penetrant selection and use depend on the criticality of the inspection, the condition of the workpiece surface, the type of processing, and the desired sensitivity.

Water-washable penetrants are designed for the removal of excess surface penetrant by water rinsing directly after a suitable penetration (dwell) time. The emulsifier is incorporated into the water-washable penetrant. When this type of penetrant is used, it is extremely important that the removal of excess surface penetrant be properly controlled to prevent overwashing, which can cause the penetrant to be washed out of the flaws.

Lipophilic and hydrophilic postemulsifiable penetrants are insoluble in water, and, therefore, are not removable by water rinsing alone. They are designed to be selectively removed from the surface of the workpiece using a separate emulsifier. The emulsifier, properly applied and left for a suitable emulsification time, combines with the excess surface penetrant to form a water-washable surface mixture, which can be rinsed from the surface of the workpiece. The penetrant that remains within the flaw is not subject to overwashing if the emulsifier is confined to the surface and if the discontinuity is tight (no mechanical rinsing).

Solvent-removable penetrants are used primarily where portability is required and to inspect localized areas. To minimize the possibility of removing the penetrant from discontinuities, the use of excessive amounts of solvent must be avoided.

Physical and Chemical Characteristics. Both fluorescent and visible penetrants, whether water-washable, postemulsifiable, or solvent-removable, must have certain chemical and physical characteristics to perform their intended functions. Principal requirements of penetrants are:

- Chemical stability and uniform physical consistency
- A flash point not lower than 95 °C (200 °F); penetrants that have lower flash points constitute a potential fire hazard.

- A high degree of wettability
- Low viscosity to permit better coverage and minimum dragout
- Ability to penetrate discontinuities quickly and completely
- Sufficient brightness and permanence of color
- Chemical inertness with materials being inspected and with containers
- Low toxicity to protect personnel
- Slow drying characteristics
- Ease of removal
- Inoffensive odor
- Low cost
- Resistance to ultraviolet light and heat fade

Emulsifiers

Emulsifiers are liquids used to render excess oily penetrant on the surface of a workpiece water washable. Emulsifiers are oil-base and water-base.

Oil-base emulsifiers function by diffusion. The emulsifier diffuses into the penetrant film and renders it spontaneously emulsifiable in water. The rate at which it diffuses into the penetrant establishes its emulsification time. Because the emulsifier is fast acting, the rinse operation should be done quickly to avoid over emulsification.

Water-base emulsifiers usually are supplied as liquid concentrates that are diluted in water to concentrations of 5 to 30% for dip-tank applications and of 0.05 to 5% for spray applications. Water-base emulsifiers function by displacing excess surface penetrant from the surface of the part by detergent action. The force of the water spray or air agitation of open dip tanks provides the scrubbing action while the detergent displaces the excess surface penetrant.

Solvent Cleaners

Solvent cleaners differ from emulsifiers in that they remove excess surface penetrant through direct solvent action. The penetrant is dissolved by the solvent. Solvent cleaners are flammable and nonflammable. Flammable cleaners are free of halogens, but are potential fire hazards. Nonflammable cleaners usually contain halogenated solvents, which render them unsuitable for some applications--usually because of their high toxicity or because they have undesirable effects on some materials.

Developers

Because the amount of penetrant that emerges from a small surface opening is minute, the visible evidence of its presence must be enhanced. Developers are used to spread the penetrant available at the defect, thus increasing the amount of light emitted, or the amount of constrast, that makes the defect visible to the unaided eye.

Developers must have the following properties/ characteristics for optimal performance.

- It must be adsorptive to maximize blotting.
- It must have fine grain size and a particle shape that will disperse and expose the penetrant at a flaw to produce strong and sharply defined indications of flaws.
- It must be capable of providing a contrast background for indications when color-contrast penetrants are used.
- It must be easy to apply.
- It must form a thin, uniform coating over a surface.
- It must be easily wetted by the penetrant at the flaw (the liquid must be allowed to spread over the particle surfaces).
- It must be nonfluorescent if used with fluorescent penetrants.
- It must be easy to remove after inspection.
- It must not contain ingredients harmful to parts being inspected or to equipment used in the inspection

operation.
- It must not contain ingredients harmful or toxic to the operator.

Four forms of developers commonly used are dry powder (Form A), water soluble (Form B), water suspendible (Form C), and nonaqueous solvent suspendible (Form D).

Dry Developers

Dry powder developers are widely used with fluorescent penetrants, but should not be used with visible-dye penetrants because they do not produce a satisfactory contrast coating on the surface of the workpiece. Ideally, dry powder developers should be light and fluffy to allow easy application and should cling to dry surfaces in a fine film. Powder adherence should not be excessive, because the amount of penetrant at fine flaws is insufficient to seep back into a thick coating.

For purposes of storage, handling, and application, powders should not be hygroscopic and should remain dry. Moisture impairs their ability to flow and dust easily, and they can agglomerate, pack, and lump up in containers and in developer chambers.

Application and Removal. Hand-processing equipment usually includes a developer station, which usually is an open tank for dry developers. Workpieces are dipped into the powder, or powder is picked up with a scoop or with the hands, and dropped onto the workpiece. Excess powder is removed by shaking and tapping the workpiece. Some powders are so light and fluffy that parts are dipped into them as easily as into a liquid.

Other effective methods of application are rubber spray bulbs and air-operated spray guns. An electrostatic-charged powder gun that can apply an extremely even and adherent coating of dry powder on metal parts also is used. For simple application--especially when only a portion of the surface of a large part is being inspected--a very soft bristle brush often is adequate.

Powder can dry the skin and irritate the lining of air passages. Operators should use rubber gloves and respirators. Modern equipment often includes an exhaust system on the developer spray booth or on the developer dust chamber, which prevents dust from escaping. Powder recovery filters often are included in such installations.

Wet Developers

Three types of wet developers are: suspensions of developer powder in water (the most widely used), aqueous solutions of suitable salts, and suspensions of powder in volatile solvents.

Water-suspendible developers can be used with both visible and fluorescent penetrants. With a fluorescent penetrant, the dried developer coating must not fluoresce or absorb or filter out black light used for inspection. Water-suspendible developers permit high-speed application of developer in mass inspection of small to medium-size workpieces using the fluorescent method. A basket of small, irregularly shaped workpieces that has gone through the steps of penetrant application, penetrant dwell, and washing can be coated with developer in one quick dip in a water suspension. This method not only is quick, but also, it provides thorough, complete coverage of all surfaces of the pieces being inspected. No dry-powder application method has all these advantages to the same degree.

Wet developer is applied just after excess penetrant is washed away and immediately before drying. After drying, surfaces are uniformly coated with a thin film of developer. Developing time is decreased because heat from the drier helps to bring penetrant back out of surface openings, and the developing action occurs immediately with the developer film already in place. Workpieces are ready for inspection in a shorter period of time, before excessive bleedout from large openings occurs, so better definition of flaw indications often is obtained.

Water-suspendible developers are supplied as a dry powder concentrate, which is then dispersed in water in recommended proportions, usually from 0.04 to 0.12 kg/L ($\frac{1}{3}$ to 1 lb/gal). The amount of powder in suspension must be carefully maintained. Too much or too little developer on the surface of a workpiece can seriously affect sensitivity.

Water-soluble developers can be used for both fluorescent and visible postemulsifiable and solvent-removable penetrants. Water-soluble developers are not recommended for use with water-washable penetrants, because of the potential to wash the penetrant from within the flaw if the developer is not very carefully controlled. Water-soluble developers are supplied as a dry powder concentrate, which is then dispersed in water in recommended proportions, usually from 0.12 to 0.24 kg/L (1 to 2 lb/gal). Advantages of this form of developer are:

- The prepared bath is completely soluble and does not require any agitation
- The developer is applied prior to drying, thus decreasing the developing time
- The dried developer film on the workpiece is completely water soluble and is easily and completely removed following inspection by simple water rinsing

Nonaqueous solvent-suspendible developers are commonly used for both the fluorescent and the visible penetrant process. This form of developer produces a white coating on the surface of the part, which yields the maximum white color contrast with the red visible penetrant indication and extremely brilliant fluorescent indication.

Nonaqueous solvent-suspendible developers are supplied in the ready-to-use condition and contain particles of developer suspended in a mixture of volatile solvents. The solvents are carefully selected for their compatibility with the penetrants. Nonaqueous solvent-suspendible developers also contain surfactants in a dispersant that coat the particles and reduce their tendency to clump or agglomerate.

Nonaqueous solvent-suspendible developers are the most sensitive form of developer used with fluorescent penetrants because the solvent action contributes to the absorption and adsorption mechanisms. In many cases where tight, small flaws occur, dry powder, water-soluble, and water-suspendible developers do not contact the entrapped penetrant. This results in the failure of the developer to create the necessary capillary action and surface tension that serve to pull the penetrant from the flaw. The nonaqueous solvent-suspendible developer enters the flaw and dissolves into the penetrant. This action increases the volume and reduces the viscosity of the penetrant.

The manufacturer must carefully select and compound the solvent mixture. There are two types of solvent-based developers: nonflammable (chlorinated solvents) and flammable (nonchlorinated solvents). Both types are widely used. Selection is based on the nature of the application and the type of alloy being inspected.

Solvent developers are sometimes applied with a paintbrush, but this is likely to result in smeared indications; application by a pressure spray can is a preferred method.

Selection of Developer

Because developers play such an important role in penetrant inspection, it is very important to select the appropriate developer for a given job. For example, on very smooth or polished surfaces, dry powder does not adhere satisfactorily, and wet developers do a better job. Conversely, on very rough surfaces dry powder is far more effective.

Following are some general rules regarding developer selection:

- Use a wet developer instead of a dry developer on very smooth surfaces.
- Use a dry developer versus a wet developer on very rough surfaces.
- Wet developers are better suited for high-production inspection of small workpieces because of their greater ease and speed of application.
- Wet developers cannot be used reliably where sharp fillets unavoidably accumulate developer, which can mask flaw indications.
- Solvent developers are effective for revealing fine, deep cracks, but are not satisfactory for finding wide, shallow flaws.
- Cleaning and reinspecting a rough surface is difficult if a wet developer was used for a prior inspection.

The developer does not produce indications but simply absorbs the penetrant already present in or at the flaw and makes it more visible.

Equipment Requirements

With the exception of a source of ultraviolet (black) light for use with fluorescent penetrants, there is no special equipment that is absolutely essential for liquid-penetrant inspection. Reasonably effective inspection can be performed with a minimum of simple and relatively crude equipment. However, this approach should be considered only when: (a) no more than a few workpieces are involved, (b) specific portions of very large workpieces are being inspected, (c) maximum sensitivity is not required, or (d) inspection must be performed in the field. Therefore, most liquid-penetrant inspection is done with equipment designed specifically for the purpose.

A variety of equipment is available. "Package units" that incorporate all the necessary stations and controls are widely used, especially where relatively small workpieces in a variety of sizes and shapes are being inspected. A typical package unit for inspection using a water-washable, fluorescent-penetrant system is shown in Fig. 2. This system is designed to process a steady flow of workpieces, which move through seven stations: application of penetrant, draining excess penetrant, water rinsing, inspection under ultraviolet light to check thoroughness of rinsing, drying, application of developer, and final ultraviolet-light inspection for flaws. The unit does not include stations for preliminary cleaning and postcleaning; these operations often are performed in another area. The equipment shown in Fig. 2 is available in a wide range of sizes and can be modified in many ways to fit specific needs. For example, if a postemulsifiable system is used, workpieces are coated with emulsifier after the penetrant has been allowed to drain and prior to rinsing.

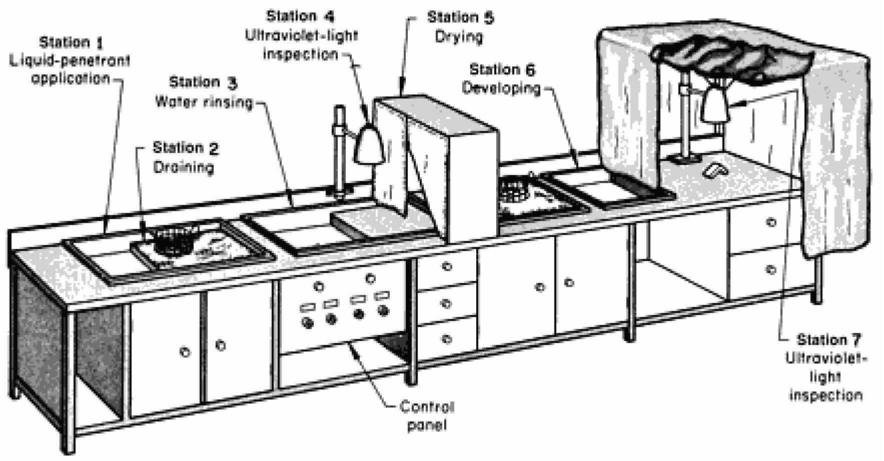


Fig. 2 Typical seven-station package equipment unit for inspecting workpieces using a water-washable, fluorescent-penetrant system

Workpiece sizes and shapes, and production quantities, are the major factors that influence the selection of equipment. An arrangement used in a foundry to process a variety of workpieces is shown in Fig. 3.

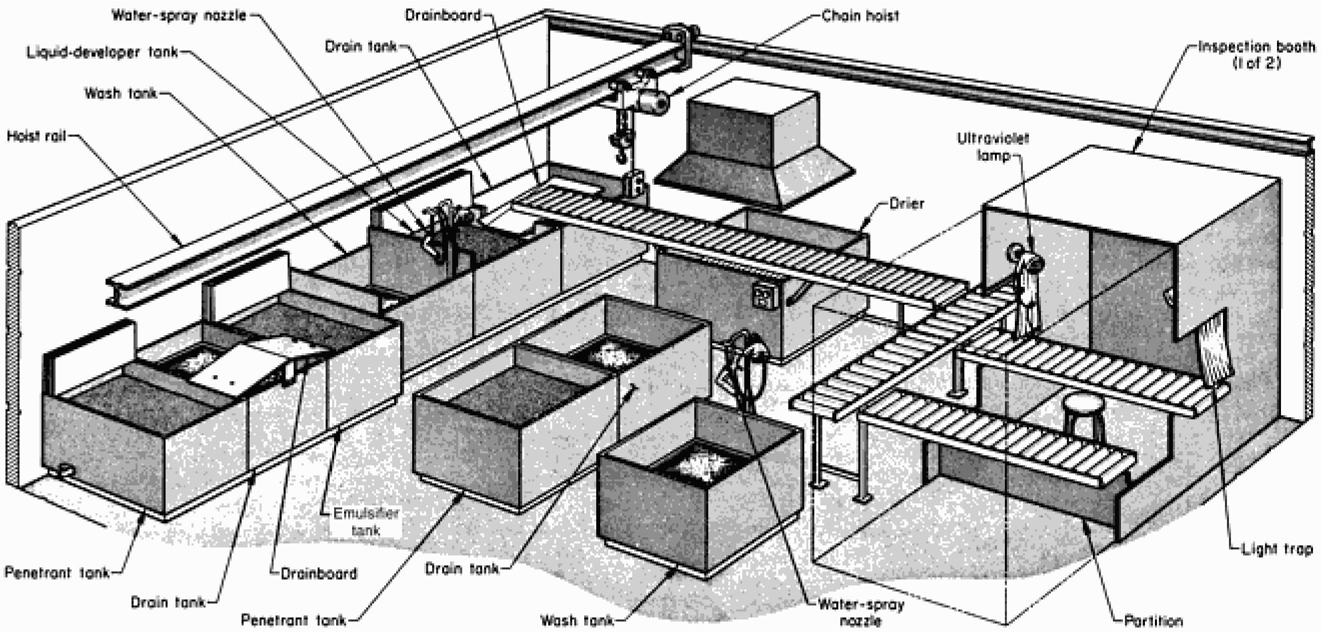

Water-spray nozzle
Liquid-developer tank
Wash tank
Hoist rail
Drainboard
Drain tank
Chain hoist
Inspection booth (1 of 2)
Ultraviolet lamp
Drier
Emulsifier tank
Penetrant tank
Drain tank
Drainboard
Penetrant tank
Drain tank
Wash tank
Water-spray nozzle
Partition
Light trap

Fig. 3 Equipment arrangement used in a foundry for liquid-penetrant inspection of a large variety of castings to rigid specifications. Castings are moved by crane and roller conveyor.

Precleaning. Regardless of the penetrant chosen, adequate precleaning of workpieces prior to penetrant inspection is absolutely necessary for accurate results. Inadequate removal of surface contamination can result in missed relevant indications because:

- The penetrant does not enter the flaw.
- The penetrant loses its ability to reveal the flaw because it reacts with a substance contained in the flaw.
- The surface immediately surrounding the flaw retains too much penetrant, which masks the true appearance of the flaw.

Also, nonrelevant (false) indications can be caused by residual materials holding penetrants.

Cleaning methods generally are classified as chemical, mechanical, solvent, and combinations of these.

Chemical cleaning methods include alkaline or acid cleaning, pickling or chemical etching, and molten salt bath cleaning.

Mechanical cleaning methods include tumbling, wet blasting, dry abrasive blasting, wire brushing, and high-pressure water or steam cleaning. Mechanical cleaning can mask flaws by smearing adjacent metal over them and by filling them with abrasive material.

Solvent cleaning methods include vapor degreasing, solvent spraying, solvent wiping, and ultrasonic immersion using solvents. Ultrasonic immersion is by far the most effective means of ensuring clean parts, but it can be a very expensive capital equipment investment.

Cleaning methods and their common uses are listed in Table 2. Major factors in the selection of a cleaning method is the type of contaminant to be removed, the type of alloy being cleaned, and knowing the chemical composition of the workpiece being cleaned. It is good practice to test the method on known flaws to ensure that it will not mask the flaws.

Table 2 Applications of various methods of precleaning for liquid-penetrant inspection

Method	Use
Mechanical	
Abrasive tumbling	Removing light scale, burrs, welding flux, braze stopoff, rust, casting mold, and core material; should not be used on soft metals such as aluminum, magnesium, and titanium
Dry abrasive grit blasting	Removing light and heavy scale, flux, stopoff, rust, casting mold and core material, sprayed coatings, and carbon deposits--in general, any friable deposit. Can be fixed or portable
Wet abrasive grit blasting	Same as dry except, where deposits are light, better surface and better control of dimensions are required
Wire brushing	Removing light deposits of scale, flux, and stopoff
High-pressure water and steam	Typically used with an alkaline cleaner or detergent; removing typical machine-shop soils such as cutting oils, polishing compounds, grease, chips, and deposits from electrical discharge machining; used when surface finish must be maintained; inexpensive
Ultrasonic cleaning	Typically used with detergent and water or with a solvent; removing adherent shop soil from large quantities of small parts
Chemical	
Alkaline cleaning	Removing braze stopoff, rust, scale, oils, greases, polishing material, and carbon deposits; typically used on large articles where hand methods are too labor intensive; also used on aluminum for gross metal removal
Acid cleaning	Strong solutions for removing heavy scale; solutions for light scale; weak (etching) solutions for removing lightly smeared metal
Molten salt bath cleaning	Conditioning and removing heavy scale
Solvent	
Vapor degreasing	Removing typical shop soil, oil, and grease; usually uses chlorinated solvents; not suitable for titanium
Solvent wiping	Same as for vapor degreasing except a hand operation; can use nonchlorinated solvents; used for localized low-volume cleaning

The surface finish of the workpiece must always be considered. When further processing is scheduled, such as machining or final polishing, or when a surface finish of 3.20 μm (125 μin.) or coarser is allowed, an abrasive cleaning method is frequently a good choice. Generally, chemical cleaning methods have fewer degrading effects on surface finish than mechanical methods (unless the chemical used is strongly corrosive to the material being cleaned). Steam cleaning and solvent cleaning rarely have any effect on surface finish.

Choice of cleaning method can be dictated by Occupational Safety and Health Administration and Environmental Protection Agency health and safety regulations. Factors to consider include quantities of materials that will be used, toxicity, filtering, neutralization and disposal techniques, and worker safety.

Penetrant Station. The principal requirement of a penetrant station is to provide a means to coat workpieces with penetrant--the entire surface for small workpieces, or over small areas of large workpieces when only local inspection is required. The station also should provide a means to drain excess penetrant back into the penetrant reservoir, unless the expendable technique is being used. Draining racks usually serve the additional purpose of providing a storage place for parts during the time required for penetration (dwell time).

Emulsifier Station. Emulsifier liquid is contained in a tank large enough to permit immersion of the workpieces, either individually or in batches. Accessory equipment includes covers to reduce evaporation and drain valves for cleanout when the bath has to be renewed. Suitable drain racks are also a part of this station, to permit excess emulsifier to drain back into the tank.

Large workpieces must be coated with emulsifier as fast as possible. Multiple spraying or copious flowing of emulsifier from troughs or perforated pipes can be used on some types of automatic equipment. For local coating of large workpieces, spraying often is satisfactory, using the expendable technique described for application of penetrant.

Rinse Station. Water rinsing (washing) of small workpieces frequently is done by hand, either individually or in batches in wire baskets. The workpieces are held in the wash tank and cleaned with a hand-held spray using water at tap pressure and temperature (water temperature should not, however, be below 10 °C, or 50 °F).

Drying Station. The recirculating hot-air drier is one of the most important equipment components. The drier must be large enough to easily handle the type and number of workpieces being inspected. Heat input, air flow, rate of movement of workpieces through the drier, and temperature control are all factors that must be balanced. The drier may be of the cabinet type illustrated in Fig. 2, or it can be designed so that the workpieces pass through on a conveyor (Fig. 3). If conveyor operation is used, the speed must be coordinated with the required drying cycle.

Developer Station. The type and location of developer station depend on whether dry or wet developer is used. For dry developer, the developer station is downstream from the drier, whereas for wet developer, it immediately precedes the drier, following the rinse station.

The dry-developer station usually consists of a simple bin containing the powder. Dried workpieces are dipped into the powder and the excess powder is shaken off. For larger workpieces that are difficult to immerse in the powder, a scoop can be used to throw powder over the surfaces, after which the excess is shaken off. The developer bin should be equipped with an easily removable cover to protect the developer from dust and dirt when not in use.

Dust-control systems are sometimes needed when dry developer is used (Fig. 4).

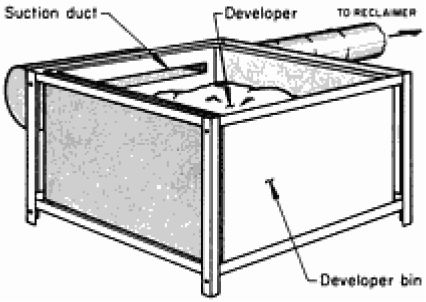


Fig. 4 Dry-developer bin equipped with dust-control and reclaimer system

The inspection station essentially is a worktable on which workpieces can be handled under proper lighting. For fluorescent methods, the table usually is surrounded by a curtain or hood to exclude most of the white light from the area (see Fig. 2). For visible penetrants, a hood is not necessary.

Black (ultraviolet) lights can consist of batteries of 100 or 400 watt lamps for area lighting, or, in small stations, can be one or two 100 watt spot lamps mounted on brackets from which they can be lifted and moved about by hand. Because of the heat given off by black lights, good air circulation is essential in black-light booths.

For automatic inspection, workpieces are moved through booths equipped with split curtains, either by hand or by conveyor (see Fig. 3).

Postcleaning Station. Postinspection cleaning often is necessary to remove all traces of penetrant and developer. Drastic chemical or mechanical methods are seldom required for postcleaning. When justified by the volume of work, an emulsion cleaning line is effective and reasonable in cost. In special circumstances, ultrasonic cleaning may be the only satisfactory way of cleaning deep crevices or small holes. However, solvents or detergent-aided steam or water is almost always sufficient. The use of steam with detergent is probably the most effective of all methods.

Selection of Penetrant System

Size, shape, and weight of workpieces, as well as number of similar workpieces to be inspected, can influence the selection of a penetrant system.

Sensitivity and Cost. The required level of sensitivity and cost usually are the most important factors in selecting a system. The methods capable of the greatest sensitivity are also the most costly. There are many inspection operations that require the ultimate in sensitivity, but there are also many where extreme sensitivity not only is not required, but also can produce misleading results.

On a practical basis, the three major penetrant systems are broken down into six systems or variations of systems. The six systems, in order of decreasing sensitivity and decreasing cost are:

1. Postemulsifiable fluorescent
2. Solvent-removable fluorescent
3. Water-washable fluorescent
4. Postemulsifiable visible
5. Solvent-removable visible
6. Water-washable visible

Table 3 compares the sensitivities and uses of the six systems.

Table 3 A comparison of penetrant systems

Water washable	Postemulsifiable	Solvent removable
Visible dye penetrants		
Lowest in sensitivity	Higher sensitivity than water washables	Where water rinse is not feasible, or desirable
Suited for large surface areas	Suited for large surface areas	For spot inspections
	Suited for large quantities of similar objects	Recommended for small areas and simple geometries
Fluorescent penetrants		
Lowest in sensitivity of fluorescent penetrants	Higher sensitivity than water washable fluorescent penetrants	Higher sensitivity than solvent-removable visible penetrant
Suited for large surface areas	Suited for large quantities of similar articles	Where water rinse is not feasible or desirable
Suited for large quantities of similar objects	Suited for wide, shallow discontinuities and tight cracks	For spot inspections
Suited for deep, narrow discontinuities	Contaminants must be removed prior to inspection	Recommended for small areas and simple geometries
Recommended for rough surfaces (i.e., sand castings)	Suited for stress, intergranular, and grinding cracks	

For environmental reasons, water washable penetrant systems are used even though the solvent system would be preferable.

Processing Cycles for Water-Washable Systems

After the workpieces have been precleaned, processing for penetrant inspection should begin immediately. A processing flow diagram for the water-washable system, from precleaning to postcleaning, is presented in Fig. 5. Time in each station, equipment used, and other factors can vary widely, depending on workpiece size and shape, production quantities of similar workpieces, and required sensitivity.

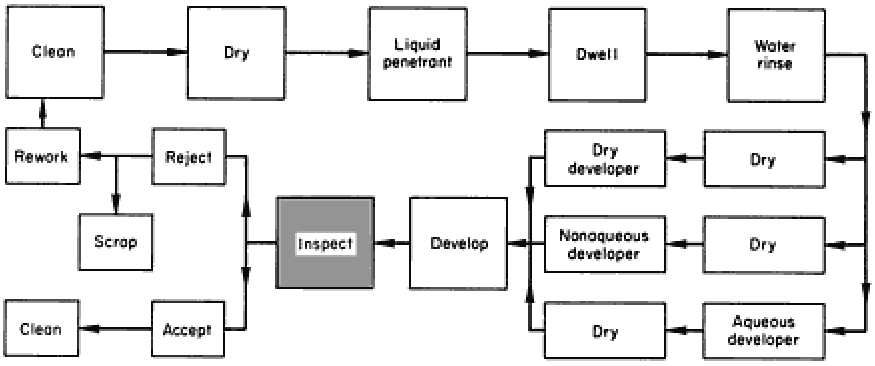


Fig. 5 Processing flow diagram for the water-washable, liquid-penetrant system

Processing Cycles for Postemulsifiable Systems

As indicated by the flow diagram in Fig. 6, the processing cycle for the postemulsifiable system is the same as for the water-washable system (see preceding description) except that the workpieces are dipped or otherwise treated with the emulsifier immediately following the dwell period that succeeds the penetrant treatment.

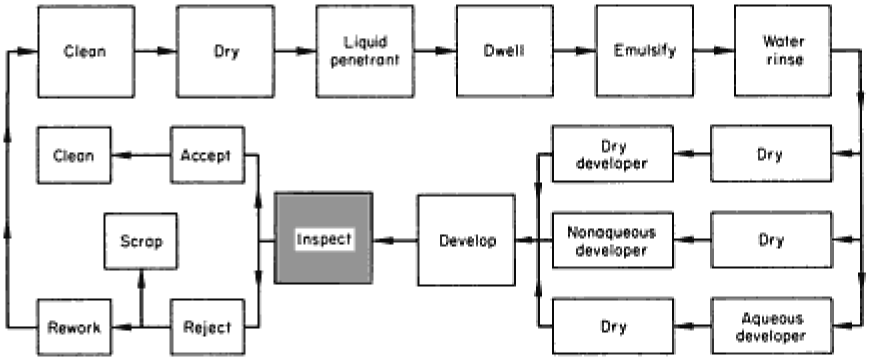

Clean
Dry
Liquid penetrant
Dwell
Emulsify
Water rinse
Clean
Accept
Dry developer
Dry
Scrap
Inspect
Develop
Nonaqueous developer
Dry
Rework
Reject
Dry
Aqueous developer

Fig. 6 Processing flow diagram for the post-emulsifiable lipophilic (oil-base) liquid-penetrant system. For hydrophilic (water-base) systems, an extra prerinse step is required between the penetrant dwell and emulsifying steps.

Processing Cycles for Solvent-Removable Systems

The basic sequence of operations for the solvent-removable, liquid-penetrant system is generally similar to that followed for the other systems. A typical sequence is shown by the flow diagram in Fig. 7. A notable difference is that with the solvent-removable system, excess penetrant very often is wiped from the workpiece.

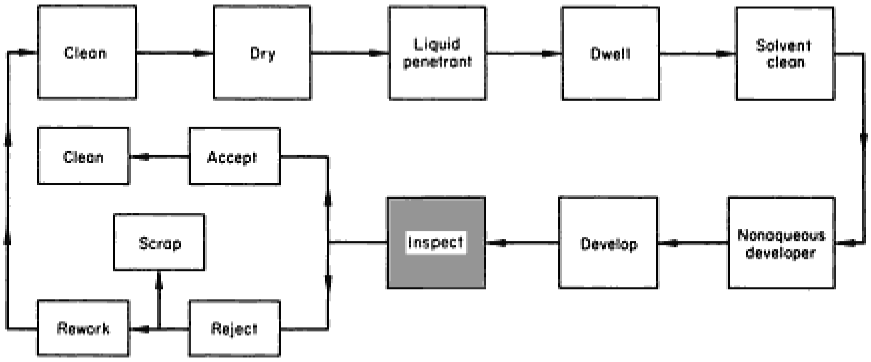

Clean
Dry
Liquid penetrant
Dwell
Solvent clean
Clean
Accept
Scrap
Inspect
Develop
Nonaqueous developer
Rework
Reject

Fig. 7 Processing flow diagram for the solvent-removable, liquid-penetrant system

In practice, however, the techniques of the solvent-removable system are likely to be quite different from those of the other systems--largely because of differences in application. The solvent-removable system is very useful when inspection must be done in areas where it is not convenient to use water.

Techniques Using Portable Equipment

Liquid-penetrant inspection is one inspection method where the testing materials can be brought to the work site when the workpiece cannot be brought to the inspection area. Portable penetrant inspection, by the solvent-removable system, is used extensively to inspect welded joints where only limited areas are being examined and where total immersion of the weldment would be impractical. In general, the methods and procedures used with portable equipment essentially are the same as those used with fixed, immersion-type inspection equipment.

Portable kits are available for both the fluorescent and the visible solvent-removable systems. The three components--cleaner, penetrant, and developer--are packaged both in bulk containers and in aerosol spray cans. The choice between spray and swabbing depends on the type and size of defect anticipated, the size of the area to be tested, and the degree of precleaning and postcleaning to be performed. Cleaning and penetrant removal is done using lint-free cloths and paper towels.

Specifications and Standards

It has not been practical to establish any type of universal standardization due to the wide variety of components and assemblies subjected to penetrant inspection, the differences in the types of discontinuities common to them, and the differences in the degree of integrity required. Generally, quality standards for the types of discontinuities detected by penetrant inspection are established by one or more of the following methods:

- Adoption of standards that have been successfully used for similar workpieces
- Evaluation of the results of penetrant inspection by destructive examination
- Experimental and theoretical stress analysis

Specifications. A specification is a document that typically delineates design and performance requirements. A specification should include the methods of inspection and the requirements based on the inspection or test procedure. However, this is difficult with penetrant inspection; wording in quality specifications often is ambiguous and meaningless.

Specifications applicable to penetrant inspection generally are divided into two broad categories: those involving materials and equipment and those concerning methods and standards. There are several standards and specifications that are in common use; some are listed in Table 4.

Table 4 Selected standards and specifications for liquid penetrant inspection

Number	Title or explanation of standard or specification
ASTM standards	
ASTM E 165	Standard Practice for Liquid-Penetrant Inspection Method
ASTM E 270	Standard Definitions of Terms Relating to Liquid-Penetrant Inspection
ASTM E 1208	Standard Method for Fluorescent Liquid-Penetrant Examination Using the Lipophilic Post-Emulsification Process
ASTM E 1209	Standard Method for Fluorescent-Penetrant Examination Using the Water-Washable Process
ASTM E 1210	Standard Method for Fluorescent-Penetrant Examination Using the Hydrophilic Post-Emulsification Process
ASTM E 1219	Standard Method for Fluorescent-Penetrant Examination Using the Solvent-Removable Process
ASTM E 1220	Standard Method for Visible-Penetrant Examination Using the Solvent-Removable Process
ASTM E 1135	Standard Test Method for Comparing the Brightness of Fluorescent Penetrants
ASTM D 2512	Compatibility of Materials with Liquid Oxygen (Impact-Sensitivity Threshold Technique)
Test for AMS-SAE specifications	
AMS 2647	Fluorescent Penetrant Inspection--Aircraft and Engine Component Maintenance
ASME specifications	
ASME-SEC V	ASME Boiler and Pressure Vessel Code Section V, Article 6
U.S. military and government specifications	
MIL-STD-6866	Military Standard Inspection, Liquid Penetrant
MIL-STD-410	Nondestructive Testing Personnel Qualifications & Certifications
MIL-I-25135	Inspection Materials, Penetrant
MIL-I-25105	Inspection Unit, Fluorescent Penetrant, Type MA-2
MIL-I-25106	Inspection Unit, Fluorescent Penetrant, Type MA-3
MIL-STD-271 (Ships)	Nondestructive Testing Requirements for Metals

Control Systems. In conjunction with the specifications listed in Table 4, several methods and several types of standards are used to check the effectiveness of liquid penetrants. One of the oldest and most frequently used methods involves chromium-cracked panels, which are available in sets containing fine, medium, and coarse cracks. Many other types of inspection standards have been produced--often for specific indications needed for a unique application.

Acceptance and rejection standards for liquid penetrant inspection are usually established for each individual item or group of items by the designer. In most cases, acceptance and rejection standards are based on experience with similar items, the principal factor being the degree of integrity required.

Magnetic-Particle Inspection

Introduction

MAGNETIC-PARTICLE INSPECTION is used to locate surface and subsurface discontinuities in ferromagnetic materials. The method is based on the fact that when a material or part being tested is magnetized, discontinuities that lie in a direction generally transverse to the direction of the magnetic field cause a leakage field to form at and above the surface of the part. The presence of the leakage field, and, therefore, the presence of the discontinuity, is detected by the use of finely divided ferromagnetic particles applied over the surface. Some of the particles are gathered and held by the leakage field. The magnetically held particles form an outline of the discontinuity and generally indicate its location, size, shape, and extent. Magnetic particles are applied over a surface either as dry particles or as wet particles in a liquid carrier such as water and oil.

Nonferromagnetic materials cannot be inspected by this method. Such materials include aluminum alloys, magnesium alloys, copper and copper alloys, lead, titanium and titanium alloys, and austenitic stainless steels.

Applications. The principal industrial uses of magnetic-particle inspection are final inspection, receiving inspection, in-process inspection and quality control, maintenance and overhaul in the transportation industries, plant and machinery maintenance, and inspection of large components.

Although in-process, magnetic-particle inspection is used to detect discontinuities and imperfections in material and parts as early as possible in the sequence of operations, final inspection is required to ensure that rejectable discontinuities and imperfections detrimental to part use and function have not developed during processing.

Advantages. The magnetic-particle method is a sensitive means to locate small, shallow surface cracks in ferromagnetic materials. Cracks large enough to be seen by the naked eye can produce an indication, but very wide cracks will not produce a particle pattern if the surface opening is too wide for the particles to bridge.

Discontinuities that do not actually break through the surface also are indicated in many instances using magnetic particle inspection within certain limitations. Fine, sharp discontinuities close to the surface (a long stringer of nonmetallic inclusions, for example) can produce an indication. Indications of deeper discontinuities are less distinct.

Limitations. The operator must be aware of certain limitations of magnetic-particle inspection. For example, thin coatings of paint and nonmagnetic coverings, such as plating, adversely affect sensitivity. Other limitations include:

- Workpiece material must be ferromagnetic.
- The direction of the magnetic field must intercept the principal plane of the discontinuity at right angles for best results. This could require two or more sequential inspections with different magnetizations.
- Demagnetization following inspection often is necessary.
- Postcleaning to remove remnants of magnetic particles and carrying solutions on the surface could be required after testing and demagnetization.
- Inspection of very large parts could require very large current.
- Local heating and burning of finished parts and surfaces at the points of electrical contact is possible if not careful.
- Experience and skill in interpreting the significance of magnetic-particle indications is necessary.

Description of Magnetic Fields

Magnetized Ring. When a magnetic material is placed across the poles of a horseshoe magnet having square ends (forming a closed or ring like assembly), the magnetic lines of force flow from the north pole through the magnetic material to the south pole (see Fig. 1a). (Magnetic lines of force flow preferentially through magnetic material rather than through nonmagnetic material or air.) The magnetic lines of force are enclosed within the ringlike assembly because no external poles exist, and iron filings or magnetic particles dusted over the assembly are not attracted to the magnet even though there are lines of magnetic force flowing through it.

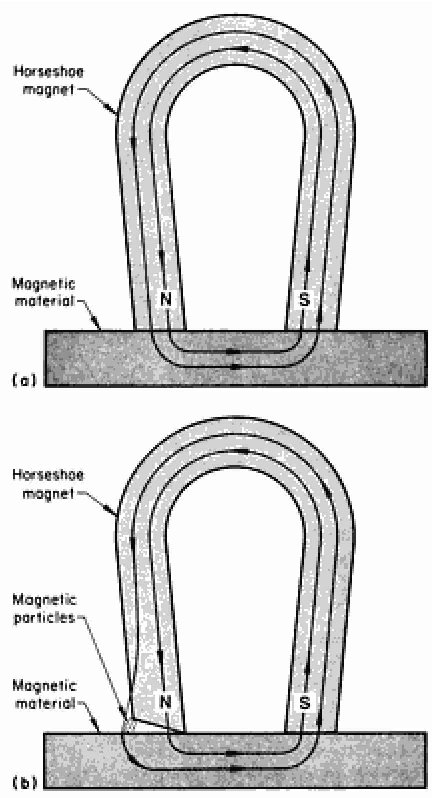


Fig. 1 (a) Horseshoe magnet with a bar of magnetic material across poles forms a closed, ringlike assembly, which will not attract magnetic particles. (b) Ringlike magnet assembly with an air gap, to which magnetic particles are attracted

If one end of the magnet is not square, leaving an air gap between the magnet end and the magnetic material, the poles still attract magnetic materials. Magnetic particles cling to the poles and bridge the gap between them, as shown in Fig. 1(b). A radial crack in a round magnetized piece creates north and south magnetic poles at the edges of the crack. Magnetic particles are attracted to the poles created by such a crack, forming an indication of the discontinuity.

The magnetic fields at cracks and other physical and magnetic discontinuities in the surface are called leakage fields. The strength of a leakage field determines the number of magnetic particles that will gather to form indications; strong indications are formed at strong fields, and vice versa. The density of the magnetic field determines its strength and is partly governed by the shape, size, and material of the part being inspected.

Magnetized Bar. A straight piece of magnetized material (bar magnet) has a pole at each end. Magnetic lines of force flow through the bar from the south pole to the north pole. Because the magnetic lines of force within the bar magnet run the length of the bar, it is said to be longitudinally magnetized or to contain a longitudinal field.

If a bar magnet is broken into two pieces, a leakage field with north and south poles is created between the pieces, as shown in Fig. 2(a). The field exists even if the fracture surfaces are brought together (see Fig. 2b). If the magnet is cracked but not broken completely into two pieces, a similar result occurs. A north and a south pole form at opposite edges of the crack, just as though the break were complete (see Fig. 2c). It is this field that attracts the iron particles that outline the crack. The strength of the poles is different from that of the completely broken pieces; it is a function of the crack depth and the width of the air gap at the surface.

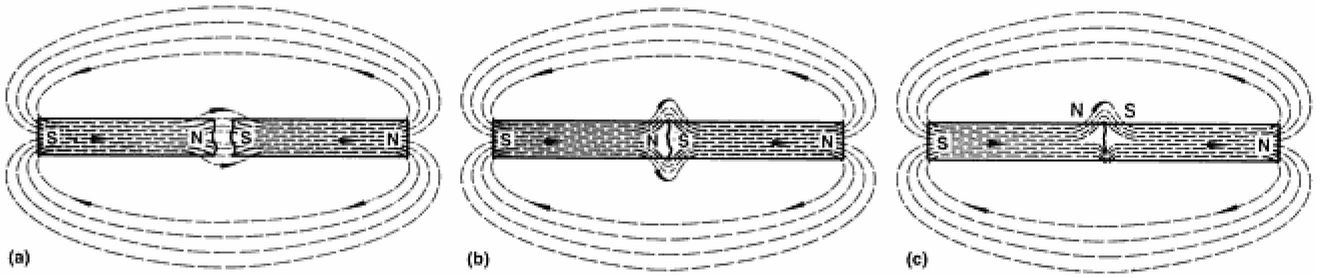


Fig. 2 Leakage fields between two pieces of a broken bar magnet (a) with magnet pieces apart, and (b) with magnet pieces together (simulating a flaw). (c) Leakage field at a crack in a bar magnet

Circular Magnetization. Electric current passing through any straight conductor such as a wire or bar creates a circular magnetic field around the conductor. The passage of current through a ferromagnetic conductor induces a magnetic field in both the conductor and surrounding space. A part magnetized in this manner is said to have a circular field or to be circularly magnetized, as shown in Fig. 3(a).

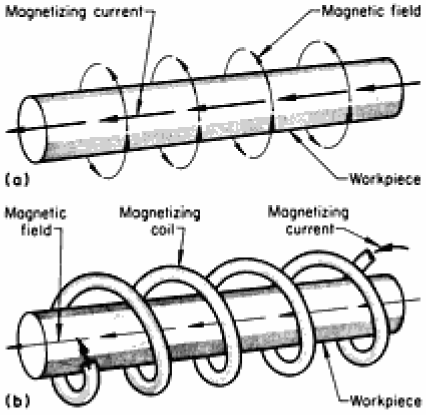


Fig. 3 Magnetized bars showing directions of magnetic field: (a) Circular. (b) Longitudinal

Longitudinal Magnetization. Electric current also can be used to create a longitudinal magnetic field in magnetic materials. When current is passed through a coil of one or more turns, a magnetic field is established lengthwise, or longitudinally, within the coil, as shown in Fig. 3(b). The nature and direction of the field around the conductor that forms the turns of the coil produce longitudinal magnetization.

Effect of Flux Direction. To form an indication, the magnetic field must approach a discontinuity at a sufficiently large angle to cause the magnetic lines of force to leave the part and return after bridging the discontinuity. An intersection approaching 90° produces the best results. For this reason, discontinuity direction, size, and shape are important. The direction of the magnetic field, and the strength of the field in the area of the discontinuity also are important for optimum results.

Figure 4(a) illustrates a condition where the current is passed through the part, causing formation of a circular field around the part. Under normal circumstances, there would be no indication of the presence of a discontinuity such as one designated "A" in Fig. 4(a) because it is regular in shape and lies in a direction parallel to that of the magnetic field. A discontinuity having an irregular shape and predominantly parallel to the magnetic field, "B," has a good chance to form a weak indication. Where the predominant direction of the discontinuity is at a 45° angle to the magnetic field, such as at "C," "D," and "E," the conditions are more favorable for detection regardless of the shape of the discontinuity. Discontinuities whose predominant directions, regardless of shape, are at a 90° angle to the magnetic field ("F," "G," and "H") produce the most pronounced indications.

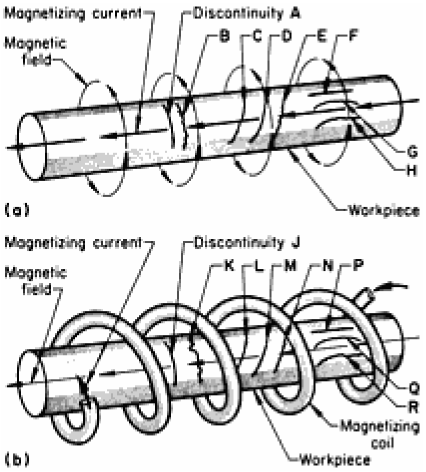


Fig. 4 Effect of direction of magnetic field or flux flow on detectability of discontinuities having various orientations. See text for discussion. (a) Circular magnetization. (b) Longitudinal magnetization

Figure 4(b) shows a bar that has been longitudinally magnetized. Discontinuities "L," "M," and "N," which are at about 45° to the magnetic field, would produce detectable indications, as they would in a circular field. Discontinuities "J" and "K" would display pronounced indications, but discontinuities "P," "Q," and "R" would probably not be detected.

Magnetiziation Methods. In magnetic-particle inspection, the magnetic particles can be applied to the part while the magnetizing current is flowing and after the current has ceased to flow, depending largely on the magnetization retention (residue magnetism) of the part. The former technique is known as the "continuous method"; the latter, as the "residual method."

If residual magnetism does not provide a leakage field strong enough to produce readable indications when magnetic particles are applied to the surface, the part must be continuously magnetized during application of particles. Consequently, the residual method can be used only on materials having sufficient retentivity; harder materials usually have higher retentivity. The continuous method is the only method used on low-carbon steels and iron having little or no retentivity.

Magnetizing Current

Both direct and alternating currents are suitable to magnetize parts for magnetic-particle inspection. Magnetic-field strength, direction, and distribution are greatly affected by the current type used for magnetization.

The fields produced by direct and alternating current have different characteristics. The important difference in magnetic-particle inspection is that fields produced by direct current generally penetrate the cross section of the part, whereas fields produced by alternating current are confined to the metal at or near the surface of the part, which commonly is known as the skin effect. Therefore, alternating current should not be used to search for subsurface discontinuities.

Direct Current. The best source of direct current is rectified alternating current. Both single-phase and three-phase alternating current are furnished commercially. Rectifiers convert reversing alternating current to unidirectional current. Rectified three-phase alternating current is nearly equivalent to straight direct current for purposes of magnetic-particle inspection. The only difference between rectified three-phase alternating current and straight direct current is a slight ripple in the value of the rectified current, amounting to only about 5% of the maximum current value.

Alternating current, which must be single-phase when used directly to magnetize a part, is used directly from commercial power lines at a frequency of 50 or 60 Hz. When used for magnetizing, line voltage is stepped down by means of a transformer to the lower voltages required. Magnetizing currents of several thousand amperes often are used at the low voltages.

One problem in using alternating current is that residual magnetism in the part might be lower than that of the magnetism generated by the peak current of the alternating-current cycle. This is because the level of residual magnetism depends on where in the cycle the current is discontinued.

Power Sources

Portable equipment is available in lightweight (16 to 41 kg, or 35 to 90 lb) power-source units that are easily transported to an inspection site. Generally, portable units are designed to use 115, 230 and 460 V alternating current, and supply 750 to 1500 A magnetizing-current outputs in half-wave or alternating current. Small, lightweight pulsed dc units that can produce up to 7000 A of magnetizing current also are available.

Mobile Units generally are mounted on wheels to facilitate transport to an inspection site. Mobile equipment usually supplies full-wave, half-wave, and alternating magnetizing-current outputs. Part inspection is accomplished by use of flexible cables, yokes, prod contacts, contact clamps, and coils. Instruments and controls are mounted on the front of the unit. Magnetizing current usually is controlled using a remote-control switch connected to the unit by an electrical cord. Quick-coupling connectors for connecting magnetizing cables are on the front of the unit.

Mobile equipment usually is powered by single-phase or three-phase, 60 Hz alternating current (230 and 460 V), and has an output range of 1500 to 10,000 A.

Stationary equipment is available in both general-purpose and special-purpose units. The general-purpose unit is primarily used in the wet method, and has a built-in tank containing a bath pump, which continuously agitates the bath and forces the fluid through hoses onto the part being inspected. Pneumatically operated contact heads, together with a rigid-type coil, provide capabilities for both circular and longitudinal magnetization. Self-contained ac and dc power supplies are available in amperage ratings from 1000 to 10,000 A.

Stationary power packs function as high-amperage, magnetizing-current sources used in conjunction with special fixtures, and with cable-wrap and clamp-and-contact techniques. Rated output varies from a customary 4000 to 6000 A to as high as 30,000 A. Higher-amperage units are used for over-all magnetization of large forgings and castings, which otherwise would require systematic prod inspection at much lower current levels. Some units feature three output circuits, which are systematically energized in rapid sequence, either electrically or mechanically, to effectively magnetize a part in several directions at virtually the same time. This allows exposure of discontinuities lying in any direction after only a single processing step.

Special-purpose stationary units are designed to handle and inspect large quantities of similar items. Generally, conveyors, automatic markers, and alarm systems are included in such units to expedite parts handling and disposition.

Methods of Generating Magnetic Fields

A basic requirement of magnetic-particle inspection is to properly magnetize the part so leakage fields created by discontinuities attract magnetic particles. While permanent magnets can accomplish this to some degree, magnetization generally is produced using electromagnets and the magnetic field associated with the flow of electric current. Basically, magnetization is derived from the circular magnetic field generated when an electric current flows through a conductor. The direction of the field is dependent on the direction of current flow.

Yokes. Two basic types of yokes commonly used for magnetizing purposes are: permanent-magnets and electromagnetic yokes. Both are hand held, and, therefore, are mobile.

Electromagnetic yokes (see Fig. 5) consist of a coil wound around a U-shape core of soft iron. The legs of the yoke are either fixed or adjustable. Adjustable legs permit changing the contact spacing and the relative angle of contact to accommodate irregular-shape parts. Unlike a permanent-magnet yoke, an electromagnetic yoke can readily be switched on or off, a feature that makes it convenient to apply and remove the yoke from the test piece.

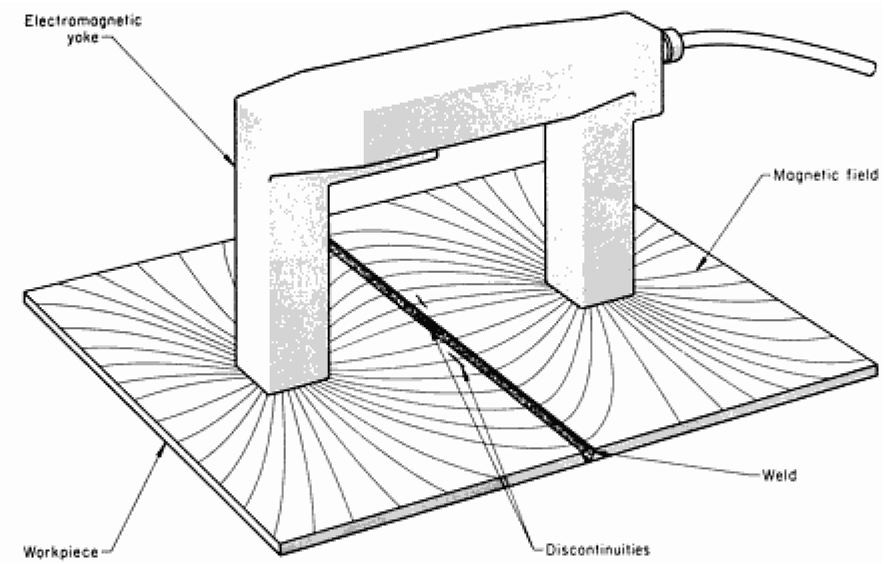


Fig. 5 Electromagnetic yoke, showing position and magnetic field to detect discontinuities parallel to a weld bead. Discontinuities across a weld bead can be detected by placing the contact surfaces of the yoke next to and on either side of the bead (rotating yoke about 90° from position shown here).

Electromagnetic yoke design is based on the use of either direct or alternating current, or both. The flux density of the magnetic field produced by the direct-current type can be changed by varying the amount of current in the coil. The direct-current type of yoke has greater penetration, whereas the alternating-current type concentrates the magnetic field at the surface of the test piece, providing good sensitivity for revealing surface discontinuities over a relatively narrow area. Yokes using alternating current for magnetization have various applications, and can be used for demagnetization as well. Discontinuities generally need to be centrally located in the area between pole pieces and oriented perpendicular to an imaginary line connecting them (see Fig. 5) to be exposed.

In operation, the part completes the magnetic path for the flow of magnetic flux. The yoke is a source of magnetic flux, and the part becomes the preferential path completing the magnetic circuit between the poles. (In Fig. 5, only those portions of the flux lines near the poles are shown.)

Coils. Single-loop and multiple-loop coils (conductors) are used for longitudinal magnetization of components (see Fig. 3b and 4b). The field within the coil has a definite direction, corresponding to the direction of the lines of force running through it. The flux density passing through the interior of the coil is proportional to the product of the current, I, in amperes, and the number of turns in the coil, N. Thus, the magnetizing force of such a coil can be varied by varying either the current or the number of turns in the coil.

Coils for large parts can be made by winding several turns of a flexible cable around the part. Care must be taken to ensure that no indications are concealed beneath the cable.

Portable magnetizing coils are available that can be plugged into an electrical outlet. These coils can be used for in-place inspection of shaft-like parts in railroad shops, aircraft-maintenance shops, and shops for automobile, truck, and tractor repair. Transverse cracks in spindles and shafts are easily detected using such coils.

Most coils used for magnetizing are short, especially those wound on fixed frames. The relation of the length of the part being inspected to the width of the coil must be considered. For a simple part, the effective over-all distance that can be inspected is 150 to 225 mm (6 to 9 in.) on either side of the coil. Thus, a part 300 to 450 mm (12 to 18 in.) long can be inspected using a normal coil approximately 25 mm (1 in.) thick. In testing longer parts, either the part must be moved at regular intervals through the coil, or the coil must be moved along the part.

The ease with which a part can be longitudinally magnetized in a coil is significantly related to the length-to-diameter (L/D) ratio of the part. This is due to the demagnetizing effect of the magnetic poles that are set up at the ends of the part. This demagnetizing effect is pronounced for L/D ratios of less than 10 to 1, and very significant for ratios of less than 3 to

1. Where the *L*/*D* ratio is extremely unfavorable, pole pieces of similar cross-sectional area can be introduced to effectively increase the length of the part and consequently improve the *L*/*D* ratio.

Central Conductors. For many tubular and ring-shaped parts, it is advantageous to use a separate conductor to carry the magnetizing current, rather than the part itself. Such a conductor, commonly referred to as a central conductor, is threaded through the inside of the part (see Fig. 6) and is a convenient way to circularly magnetize a part without the need to make direct contact to the part itself. Central conductors are made of solid and tubular nonmagnetic and ferromagnetic materials that are good electrical conductors.

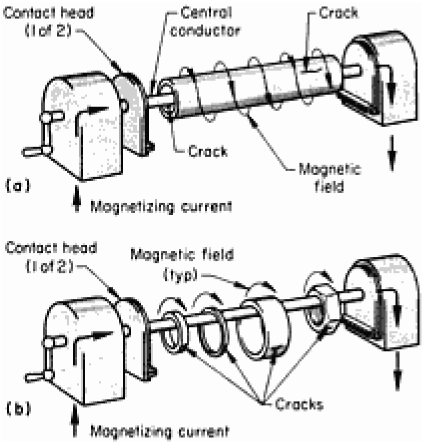


Fig. 6 Use of central conductors for circular magnetization of (a) long hollow cylindrical parts and (b) short hollow cylindrical and ringlike parts to detect discontinuities on inner and outer surfaces

The basic rules regarding magnetic fields around a circular conductor carrying direct current are:

- The magnetic field outside a conductor of uniform cross section is uniform along the length of the conductor.
- The magnetic field is 90° to the path of the current through the conductor.
- The flux density outside the conductor varies inversely with the radial distance from the center of the conductor.

Direct-Contact Method. For small parts having no openings through the interior, circular magnetic fields are produced by direct contact to the part. Parts are clamped between contact heads (head shot), generally on a bench unit (see Fig. 7) that incorporates the source of current. A similar unit can be used to supply the magnetizing current to a central conductor (see Fig. 6).

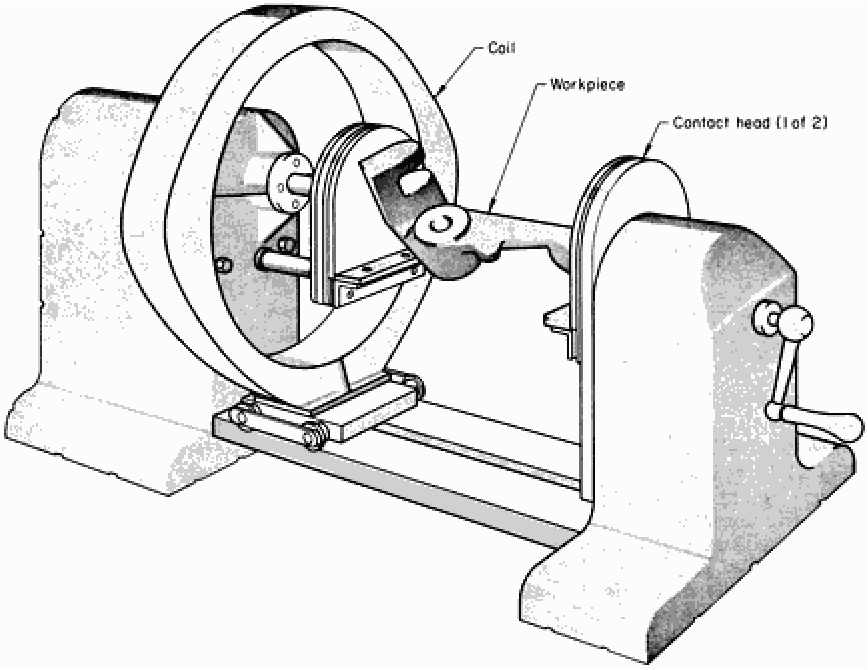

Coil
Workpiece
Contact head (1 of 2)

Fig. 7 Bench unit used to circularly magnetize workpieces clamped between contact heads (direct-contact, head-shot method). The coil on the unit can be used for longitudinal magnetization.

Contact heads must be constructed so the surfaces of the part are not damaged--either physically by pressure, or structurally by heat from arcing and from high resistance at the points of contact. Such heat can be especially damaging to hardened surfaces such as bearing races.

For complete inspection of a complex part, it could be necessary to attach clamps at several points on the part or to wrap cables around the part to get fields in the proper directions at all points on the surface. This often requires several magnetizations. The need for multiple magnetizations can be minimized by using the overall magnetization method, multidirectional magnetization, and induced-current magnetization.

Prod Contacts. Magnetization often is done using prod contacts to inspect large and massive parts too bulky to be put into a unit having clamping contact heads. The method passes current directly through the part or through a local portion of it (see Fig. 8). Such local contacts do not always produce true circular fields, but are very convenient and practical in many applications; prod contacts often are used in magnetic-particle inspection of large castings and weldments.

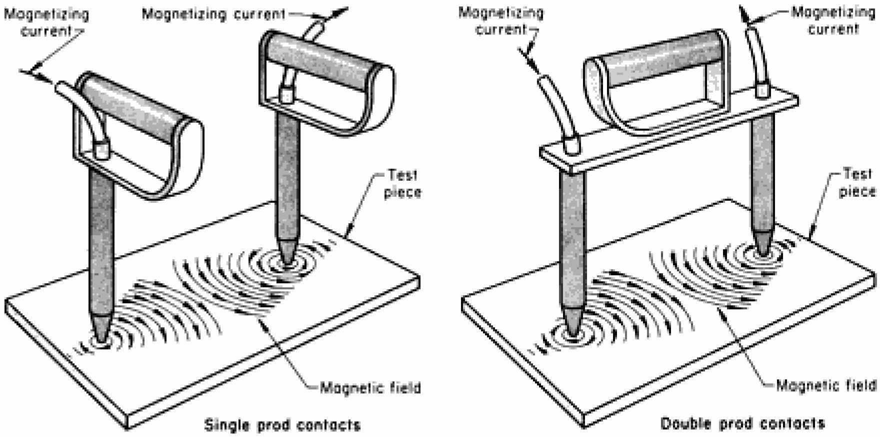

Magnetizing current
Magnetizing current
Test piece
Magnetic field
Single prod contacts
Magnetizing current
Magnetizing current
Test piece
Magnetic field
Double prod contacts

Fig. 8 Single and double prod contacts. Discontinuities are detected by a magnetic field generated between the

prods.

Prod contacts have many advantages. Easy portability makes them convenient to use for field inspection of large tanks and welded structures. Sensitivity to defects lying wholly below the surface is greater with this method of magnetization than with any other, especially when half-wave current is used in conjunction with dry powder and the continuous method of magnetization.

The use of prod contacts has some limitations:

- Suitable magnetic fields exist only between and near the prod contact points. These points are seldom more than 300 mm (12 in.) apart, and usually much less. Therefore, it sometimes is necessary to relocate the prods so the entire surface of a part can be inspected.
- Interference of the external field that exists between the prods sometimes makes observation of pertinent indications difficult. The strength of the current that can be used is limited by this effect.
- Great care must be used to avoid burning the part under the contact points. Burning can be caused by dirty contacts, insufficient contact pressure, and excessive currents.

Induced current provides a convenient method to generate circumferential magnetizing current in ring-shaped parts without making electrical contact. This is accomplished by properly orienting the ring within a magnetizing coil such that it links or encloses lines of magnetic flux (flux linkage), as shown in Fig. 9(a). As the level of magnetic flux changes (increases or decreases), a current flows around the ring in a direction opposing the change in flux level. The magnitude of this current depends on the total flux linkages, rate of flux-linkage changes, and the electrical impedance associated with the current path within the ring. Increasing the flux linkages and the rate of change increases the magnitude of current induced in the ring. The circular field associated with this current takes the form of a toroidal magnetic field that encompasses all surface areas on the ring and that is conducive to revealing circumferential types of discontinuities. This is shown schematically in Fig. 9(b).

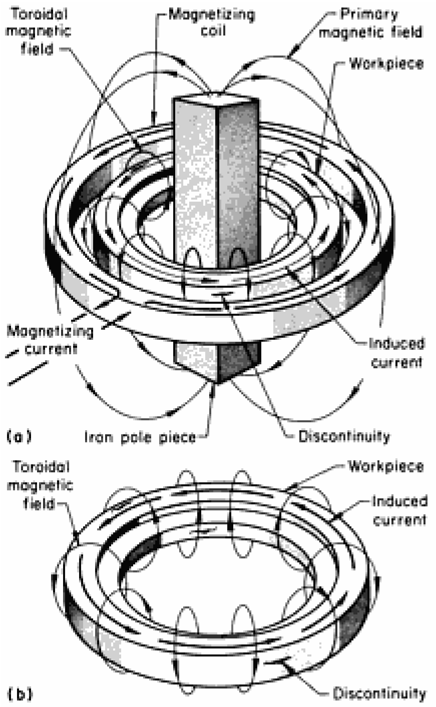


Fig. 9 Induced-current method of magnetizing a ring-shape part. (a) Ring being magnetized by induced current. Current direction corresponds to decreasing magnetizing current. (b) Resulting induced current and toroidal magnetic field in a ring

The choice of magnetizing current for the induced-current method depends on magnetic properties of the part to be inspected. In instances where the residual method is applicable, such as for most bearing races and similar parts having high magnetic retentivity, direct current is used to magnetize. The rapid interruption of the current by quick-break circuitry results in a rapid collapse of the magnetic flux and the generation of a high-amperage, circumferentially directed single pulse of current in the part. Thus, the part is residually magnetized with a toroidal field, and subsequent application of magnetic particles produces indications of circumferentially oriented discontinuities.

A similar type of current of opposite polarity and lower amplitude is associated with the increasing flux due to the rapidly rising current, but in this case, only that current generated by the sudden breaking of the direct current serves a useful purpose.

Passing an alternating current through a conductor generates a fluctuating magnetic field as the level of magnetic flux rapidly changes from a maximum value in one direction to an equal value in the opposite direction. This is similar to the current that flows in a single-shorted-turn secondary of a transformer. The alternating induced current in conjunction with the continuous method renders the method applicable for processing magnetically soft, or less retentive, parts.

The induced-current method, in addition to eliminating the possibility of damaging the part, also is capable of magnetizing in one operation parts that otherwise would require more than one head shot. Two examples of this type of part are illustrated in Fig. 10 and 11. These parts cannot be completely processed by one head shot to reveal circumferential defects, because regions at the contact points are not properly magnetized. Therefore, a two-step inspection process is required for full coverage, with the part rotated approximately 90° prior to the second step. Conversely, the induced-current method provides full coverage in one processing step. The disk-shaped part shown in Fig. 11 presents an additional problem when the contact method is used to reveal circumferential defects in the vicinity of the rim. Even when a two-step process is used, as with the ring in Fig. 10, the primary current path through the part might not develop a circular field of sufficient magnitude in the rim area. The induced current can be selectively concentrated in the rim area by proper polepiece selection to provide full coverage (rim area) in a single processing step. The pole pieces depicted in Fig. 11(b) are hollow and cylindrical, with one on each side of the disk. The pole pieces direct the magnetic flux through the disk such that the rim is the only portion constituting a totally enclosing current path.

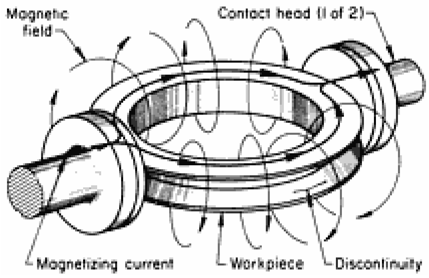


Fig. 10 Current and magnetic-field distribution in a ring being magnetized with a head shot. Because regions at contact points are not magnetized, two operations are required for full coverage. With use of the induced-current method, parts of this shape can be completely magnetized in one operation.

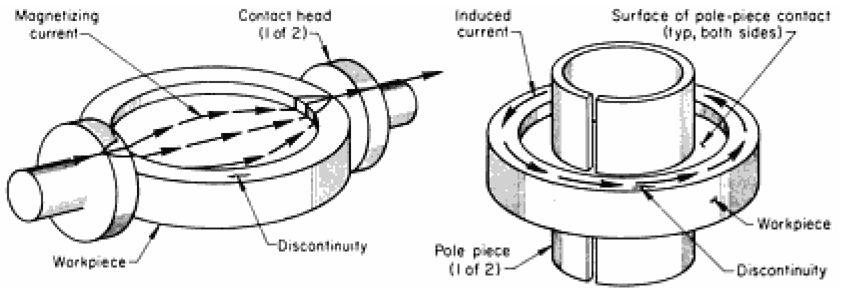


Fig. 11 Current paths in a rimmed disk-shape part magnetized by a head shot and by induced current. (a) Head-shot magnetization. (b) Induced-current magnetization

Pole pieces used in conjunction with this method are preferably constructed of laminated ferromagnetic material. This minimizes the flow of eddy currents within the pole pieces, which detract from the induced (eddy) current developed within the part being processed. Pole pieces also can be made of rods, wire-filled nonconductive tubes, and thick-wall pipe, saw cut to break up the eddy-current path.

Magnetic Particles and Suspending Liquids

Magnetic particles are classified according to the vehicle by which they are carried to the part: by air (dry-particle method) and by a liquid (wet-particle method). Magnetic particles consist of fine iron; black, brown, and red iron oxide (magnitite Fe_3O_4); brown iron oxide (γFe_2O_3), ferrospinel ferrites ($Ni_xFe_2O_4$), and some nickel alloys. Important particle characteristics include magnetic properties, size, shape, density, mobility, and degree of visibility and contrast.

Magnetic Properties. Particles used for magnetic-particle inspection should have high magnetic permeability so they can be readily magnetized by the low-level leakage fields that occur around discontinuities and can be drawn by these fields to discontinuities to form readable indications. (The fields at very fine discontinuities can be extremely weak.) Particles also should have low coercive force and low retentivity.

Effect of Particle Size. Large, heavy particles are not likely to be arrested and held by weak fields when moving over a part surface, but fine particles are held by very weak fields. However, extremely fine particles also can adhere to surface areas where there are no discontinuities (especially if the surface is rough) and form confusing backgrounds. Coarse, dry particles fall too fast and are likely to bounce off the part surface without being attracted by the weak leakage fields at imperfections. Finer particles can adhere to fingerprints, rough surfaces, and soiled or damp areas, thereby obscuring indications.

Effect of Particle Shape. Particle shape can be spherical, needlelike, and rodlike in form. Elongated needles tend to develop into little magnets with north-south poles, and, therefore, form into distinct, well-defined patterns, which provide a more clear indication of the presence of a weak magnetic field. However, there is an optimum elongation aspect ratio for particles. The ability of dry particles to flow freely and to form uniformly dispersed clouds of powder that will spread evenly over a surface is a necessary characteristic for rapid and effective dry-powder testing. The behavior of wet powder (suspensions) is less dependent on particle shape.

Visibility and contrast are enhanced by using particles with colors that make them easy to see against the color of the surface of the part being inspected. The natural color of the metallic powders used in the dry method is silver gray, but pigments are used to color them. The colors of particles for the wet method are limited to the black and red of the iron oxides commonly used as the base for wet particles.

For increased visibility, particles are coated with fluorescent pigment by the manufacturer. Inspection is conducted in total or partial darkness, using ultraviolet light to activate the fluorescent dyes. Inspected surfaces should be illuminated with a minimum of 1000 $\mu W/cm^2$ of black light, with a maximum of 2 ftc of general visible light at the inspection station. Fluorescent magnetic particles are available for use with both wet and dry methods. The fluorescent wet method is more common.

Dry particles are available in a variety of colors, some of them fluorescent. Color-contrast powders should be viewed in ordinary light of a minimum of 100 ftc at the inspection station. Dry particles are most sensitive for use on very rough surfaces and for detecting flaws beneath the surface. They are ordinarily used with portable equipment. Reclaiming and reusing dry particles is not recommended.

Wet particles are best suited for detection of fine discontinuities such as fatigue cracks. Wet particles commonly are used in stationary equipment where the bath can remain in use until contaminated or until the properties of the particles are exhausted. They also are used in field operations with portable equipment, but the bath should be agitated constantly.

Oil Suspending Liquid. The oil used as a suspending liquid for magnetic particles should be an odorless, well-refined light petroleum distillate of low viscosity and a high flash point. Oil viscosity should not exceed 0.03 cm^2/s (3 cSt) when tested at 38 °C (100 °F), and must not exceed 0.05 cm^2/s (5 cSt) when tested at the temperature prevailing at the point on the part being inspected. Above 0.05 cm^2/s, the movement of magnetic particles in the bath is sufficiently retarded to have a definite effect in reducing buildup, and therefore visibility, of an indication of a small discontinuity. Parts should be precleaned to remove oil and grease because oil from the surface builds up in the bath and increases its viscosity.

Water Suspending Liquid. The use of water instead of oil for magnetic-particle, wet-method baths reduces costs and eliminates bath flammability. Water-suspendible particle concentrates include the necessary wetting agents, dispersing agents, rust inhibitors, and antifoam agents.

Strength of the bath is a major factor in determining the quality of the indications obtained. The proportion of magnetic particles in the bath must be maintained at a uniform level. The strength of indications varies with varying concentration, which could cause misinterpretation of indications. Fine indications can be missed entirely with a weak bath. High concentrations produce a confusing background and excessive adherence of particles at external poles, which interferes with distinct indications of extremely fine discontinuities.

The best method to ensure optimum bath concentration for any given combination of equipment, bath application, and type of part and discontinuities involved is to test the bath using parts with known discontinuities. Bath strength can be adjusted until satisfactory indications are obtained. This bath concentration can then be adopted as standard for similar conditions.

Bath concentration can be measured reasonably accurately using the settling test. In the test, 100 mL (0.03 gal) of well-agitated bath is placed in a pear-shape centrifuge tube. The volume of solid material that settles out after a predetermined interval (usually 30 min) is measured on the graduated cylindrical part of the tube. Dirt in the bath also will settle and usually shows as a separate layer on top of the oxide. The layer of dirt usually is easily distinguishable because it is different in color from the magnetic particles.

Ultraviolet Light

A mercury-vapor lamp is a convenient source of ultraviolet light, emitting a light spectrum that has several intensity peaks within a wide band of wavelengths. When used for a specific purpose, emitted light is passed through a suitable filter so only a relatively narrow band of ultraviolet wavelengths is available. For example, a band in the long-wave ultraviolet spectrum is used for fluorescent liquid-penetrant or magnetic-particle inspection.

Fluorescence is the quality of an element or combination of elements to absorb the energy of light at one frequency and emit light of a different frequency. Fluorescent materials used in liquid-penetrant and magnetic-particle inspection are combinations of elements selected to absorb light in the peak energy band of the mercury-vapor lamp fitted with a Kopp glass filter. This peak occurs at about 365 nm (14.4 μin.). The ability of fluorescent materials to emit light in the greenish-yellow wavelengths of the visible spectrum depends on the intensity of ultraviolet light at the workpiece surface.

Detectable Discontinuities

The usefulness of magnetic-particle inspection in the search for discontinuities or imperfections depends on exactly what types of discontinuities the method is capable of finding. Of importance are the size, shape, orientation, and location of the discontinuity, with respect to its ability to produce leakage fields.

Surface Discontinuities. The largest and most important type of discontinuities consists of those that are exposed to the surface. Surface cracks or discontinuities are effectively located using magnetic particles. Surface cracks, such as those shown in Fig. 12, also are more detrimental to the service life of a component than are subsurface discontinuities, and, therefore, they are more frequently the object of inspection.

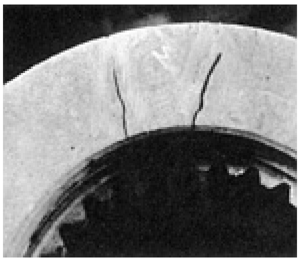


Fig. 12 Magnetic particle indications of cracks in a large cast splined coupling

Magnetic-particle inspection is capable of locating seams, laps, quenching and grinding cracks, and surface ruptures in castings, forgings, and weldments. The method also can detect surface fatigue cracks developed during service. Magnetizing and particle-application methods can be critical in certain instances, but in most applications the requirements are relatively easily met, because leakage fields usually are strong and highly localized.

To successfully detect a discontinuity, there must be a field of sufficient strength in a generally favorable direction to produce strong leakage fields. For maximum detectability, the field generated in the part should be at right angles to the length of a suspected discontinuity (see Fig. 4). This is especially true if the discontinuity is small and fine.

Subsurface discontinuities comprise those voids or nonmetallic inclusions that lie just beneath the surface. Nonmetallic inclusions are present in all steel products to some degree. They occur as scattered individual inclusions, or they may be aligned in long stringers. These discontinuities usually are very small and cannot be detected unless they lie very close to the surface because they produce highly localized but rather weak fields.

Nonrelevant Indications

Nonrelevant indications are true patterns caused by leakage fields that do not result from the presence of flaws. The term "false indications" is sometimes used to describe this type of indication, because the indication falsely implies the presence of a flaw, even though the particle buildup actually results from a leakage field. There are several possible causes of nonrelevant indications, which require evaluation but should not be interpreted as flaws.

Demagnetization after Inspection

All ferromagnetic materials retain a residual magnetic field to some degree after being magnetized. This field is negligible in magnetically soft metals, but in harder metals, it can be comparable to the intense fields associated with the special alloys used for permanent magnets.

It is not always necessary to demagnetize parts, but it is essential in many cases, even though it is costly and time consuming. The degree of difficulty in demagnetization depends on the type of metal. Metals having high coercive force are the most difficult to demagnetize. High retentivity is not necessarily related directly to high coercive force, so the strength of the retained magnetic field is not always an accurate indicator of the ease of demagnetizing.

There are several reasons to demagnetize a part after magnetic-particle inspection, or after any other magnetization. Demagnetize if:

- The part is used in an area where a residual magnetic field interferes with the operation of instruments sensitive to magnetic fields, or where it can affect the accuracy of instrumentation incorporated in an assembly that contains the magnetized part.
- Chips might adhere to the surface during subsequent machining and adversely affect surface finish, dimensions, and tool life.
- Chips might adhere to the surface during cleaning operations and interfere with subsequent operations such as painting and plating.
- Abrasive particles might be attracted to magnetized parts, such as bearing surfaces, bearing raceways, and gear teeth, resulting in abrasion and galling, and obstruction of oil holes and grooves.
- Strong residual magnetic fields can deflect the arc away from the point at which it should be applied during some arc-welding operations.
- A residual magnetic field in a part can interfere with remagnetization of the part at a field intensity too low to overcome the remanent field in the part.

Demagnetization might not be necessary if:

- Parts are made of magnetically soft steel having low retentivity; such parts usually will become demagnetized as soon as they are removed from the magnetizing source
- The parts are subsequently heated above their Curie point and consequently lose their magnetic

properties
- The magnetic field is such that it will not affect the function of the part in service
- The part is to be remagnetized for further magnetic-particle inspection or for some secondary operation in which a magnetic plate or chuck may be used to hold the part.

The last reasons for demagnetizing and not demagnetizing seem to be contradictory. The establishment of a longitudinal field after circular magnetization negates the circular field because two fields in different directions cannot exist in the same part at the same time. If the magnetizing force is not of sufficient strength to establish the longitudinal field it should be increased, or other steps taken to ensure that the longitudinal field actually has been established. The same is true in changing from longitudinal to circular magnetization. If the two fields (longitudinal and circular) are applied simultaneously, a field is established that is a vector combination of the two in both strength and direction. However, if the fields are impressed successively, the last field applied, if strong enough to establish itself in the part, destroys the remanent field from the previous magnetization.

Magnetic Field Testing

Introduction

MAGNETIC FIELD TESTING includes some widely used nondestructive evaluation methods to inspect magnetic materials for defects such as cracks, voids, and inclusions. Magnetic methods also are used to assess other material properties, such as grain size, texture, and hardness. Because of this diversion of applications, it is natural to divide the field of magnetic materials testing into two parts, one directed toward defect detection and characterization and the other aimed at material properties measurements.

All magnetic flaw-detection methods rely in some way on the detection and measurement of the magnetic flux leakage field near the surface of the material, which is caused by the presence of the flaw. Material properties characterization methods rely on bulk measurements of the hysteretic properties of material magnetization or of some related phenomenon, such as Barkhausen noise.

Principles of Magnetic Leakage Field Testing

Origin of Defect Leakage Fields. Figure 1 illustrates the origin of the flaw leakage field. A uniformly magnetized rod, shown in Fig. 1(a), consists of a large number of elementary magnets aligned with the direction of magnetization. At the surfaces, magnetic poles are uncompensated and produce a magnetic field in the region surrounding the specimen; flux lines connect uncompensated elementary poles.

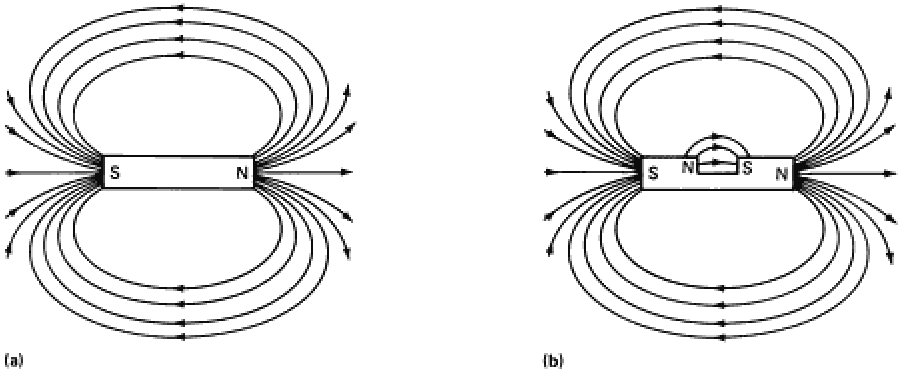


Fig. 1 Origin of defect leakage fields. (a) Magnetic flux lines of a magnet without a defect. (b) Magnetic flux lines of a magnet with a surface defect

If a slot is cut in the rod, as illustrated in Fig. 1(b), the poles on the surface of the slot are now also uncompensated and produce a localized magnetic field near the slot. The additional magnetic field represented by the extra flux lines is the leakage field associated with the slot.

Generation of a Magnetic Field. In some ferromagnetic materials, the residual field (the field that remains after removal of an external magnetizing field) often is adequate for surface flaw detection. In practice, however, residual magnetization is rarely used because use of an applied magnetizing field ensures that the material is in the required magnetic state and because applied fields provide more flexibility. (It is possible to produce high or low flux density.)

Control of the strength and direction of the magnetization is useful to improve flaw detectability and to discriminate among different types of flaws. In general, the magnitude of the magnetization should be selected to maximize the flaw leakage field with respect to other field sources that might interfere with flaw detection; optimum magnetization usually is difficult to determine in advance of a test and is often approached by trial-and-error experimentation. The direction of the field should be perpendicular to the largest flaw dimension to maximize the effect of the flaw on the leakage field.

A magnetic field can be generated in a specimen either directly or indirectly. In direct magnetization, current is passed directly through the part. With the indirect approach, magnetization is induced by placing the part in a magnetic field that is generated by an adjacent current conductor or permanent magnet. Methods of magnetizing a part both directly and indirectly are illustrated schematically in Fig. 2.

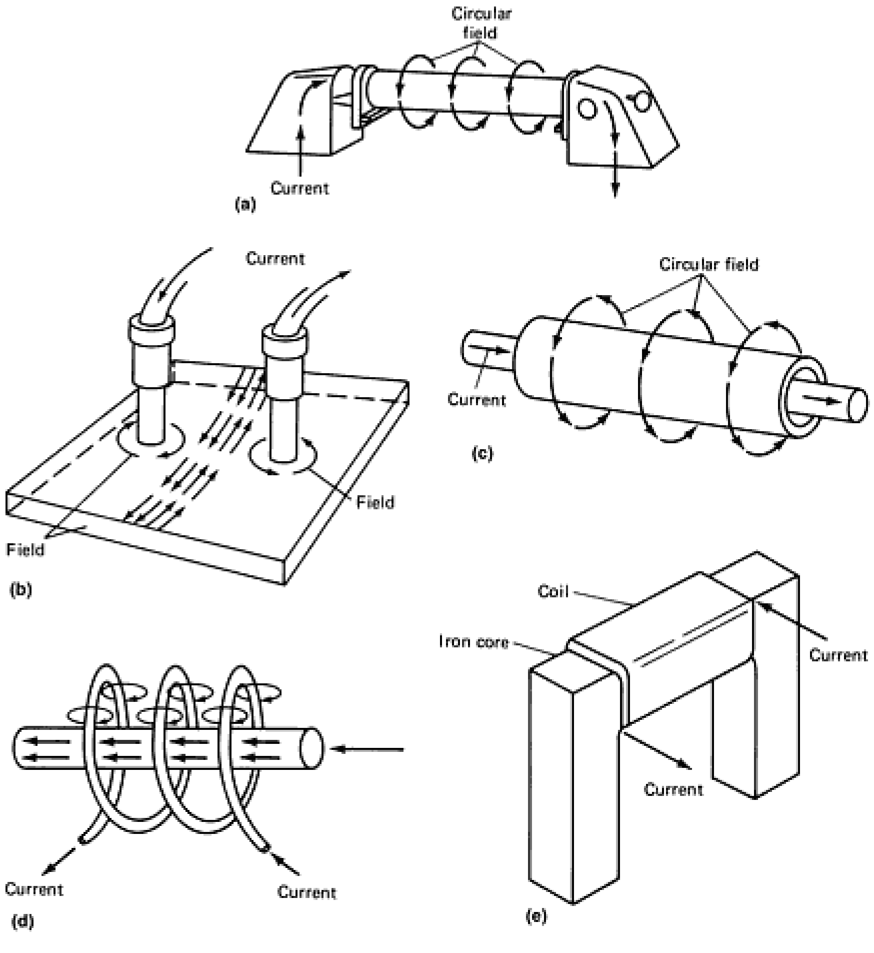


Fig. 2 Methods of magnetization. (a) Head-shot method. (b) Magnetization with prods. (c) Magnetization with a central conductor. (d) Longitudinal magnetization. (e) Yoke magnetization

The flaw leakage field can be detected using magnetic field sensors, such as the inductive coil and the Hall effect device.

The inductive coil sensor is based on Faraday's law of induction, which states that the voltage induced in the coil is proportional to the number of turns in the coil multiplied by the time rate of change of the flux threading the coil.

Detection of a magnetostatic field requires that the coil be in motion so that the flux through the coil changes with time. The principle is illustrated in Fig. 3, where the coil is oriented to sense the change in flux parallel to the surface of the specimen. Figure 4 shows the flux density typical of the leakage field from a slot and corresponding signal search as in Fig. 3.

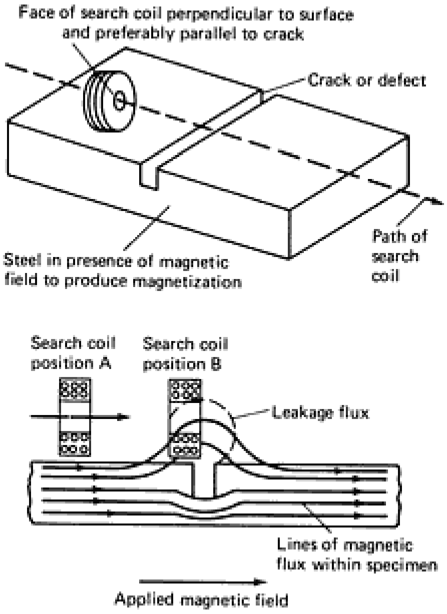

Face of search coil perpendicular to surface and preferably parallel to crack
Crack or defect
Path of search coil
Steel in presence of magnetic field to produce magnetization
Search coil position A
Search coil position B
Leakage flux
Lines of magnetic flux within specimen
Applied magnetic field

Fig. 3 Flux leakage measurement using a search coil

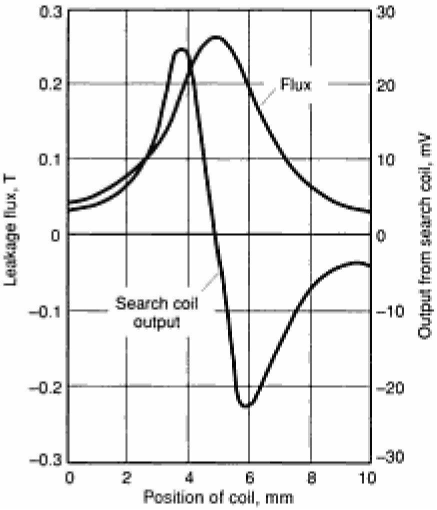


Fig. 4 Leakage flux and search coil signal as a function of position

While an inductive coil measures flux gradient, a Hall effect sensor directly measures the component of the flux itself in the direction perpendicular to the sensitive area of the device. A Hall effect sensor can be scanned over the surface to be inspected at any rate because its response does not depend on probe motion. Hall effect sensors are more difficult to fabricate, are more fragile, and require more complex electronics than coil sensors.

Other magnetic field sensors include the flux gate magnetometer, magnetoresistive sensors, magnetic resonance sensors, and magneto-graphic sensors (in which the magnetic field at the surface of a part is registered on a magnetic tape pressed onto the surface).

Analysis of Leakage Field Data. Most leakage-field testing applications require flaw detection and an estimate of the severity.

Flaw characterization is based on the relation of leakage field signal amplitude to flaw size (and depth). Therefore, signal amplitude is a direct measure of flaw severity. This empirical method works well in situations where all flaws have approximately the same shape and where calibration shows that signal amplitude is proportional to the size parameter of concern. A more careful analysis of the relationship between signal and flaw characteristics is required in situations where flaw size varies (such as corrosion pits in steel tubing) and where different types of flaws (such as cracks and pits) are present in the same part to avoid serious errors.

Principles of Magnetic Characterization of Materials

Metallurgical and Magnetic Properties. Metallurgical properties of ferromagnetic materials, such as crystallographic phase, chemical composition, and microstructure, affect their magnetic characteristics, which makes it possible to use magnetic measurements to monitor properties. Some parameters, such as grain size and orientation, dislocation density, and the existence of precipitates, are closely related to measurable characteristics of magnetic hysteresis; that is, to the behavior of the flux density, B, induced in a material as a function of the magnetic field strength, H.

Other magnetic properties, such as saturation magnetization, which is the maximum value B can achieve, and Curie temperature, at which there is a transition to a nonmagnetic state, are less dependent on microstructure, but are sensitive to such factors as crystal structure and chemical composition.

A Hall effect probe is used to measure magnetic field strength parallel to the surface of a part. A signal generator provides a low-frequency magnetizing field, typically of the order of a few Hertz, and the output of the flux measuring coil is integrated over time to give the flux density in the material.

Another magnetic testing method measures Barkhausen noise. As the magnetic field strength, H, is varied at a very slow rate, discontinuous jumps in the magnetization of the material occur during certain portions of the hysteresis cycle. The jumps are associated with the sudden growth of a series of magnetic domains that have been temporarily stopped from further growth by obstacles such as grain boundaries, precipitates, and dislocations. Therefore, Barkhausen noise is dependent on microstructure and can be used independently of hysteresis measurements, or in conjunction with such measurements, as another method of magnetic testing.

Applications

Flaw Detection. Perhaps the most prevalent use of the flux leakage method is widely used to inspect ferromagnetic tubular products, such as gas pipelines, down hole casing, and a variety of other forms of steel piping. The technique is highly developed for use in petroleum-industry applications, such as inspection of large-diameter pipelines.

In most such tools, sensors are the inductive coil type, oriented to measure the axial component of the leakage field gradient. Data usually are recorded on magnetic tape as the system is propelled down a section of pipe. The recorded signals are compared with those from calibration standards to interpret flaw indications in terms of flaw type and size.

In addition to systems for inspecting rotationally symmetric cylindrical parts, flux leakage inspection is applied to irregular components, such as gear teeth and artillery projectiles.

The flux leakage method also is used to inspect ropes and cables made of strands of ferromagnetic material. One approach is to induce magnetization in the piece by means of an encircling coil energized by a direct current. With this method, the leakage field associated with broken strands is measured using a Hall effect probe or an auxilliary sensor coil.

Another area that uses the flux leakage method is inspection of rolling-element antifriction bearings. A schematic illustration of the method as applied to an inner bearing race is shown in Fig. 5. In this application, the part is magnetized by an electromagnet, as indicated in Fig. 5(a). The race is rotated by a spindle, and the surface is scanned using an induction coil sensor. The active portion of the raceway is inspected by incrementally indexing the sensor across the raceway. Magnetizing fields are applied in the radial and circumferential orientations. Radial field inspection works best for surface flaws, while circumferential field inspection shows greater sensitivity to subsurface flaws.

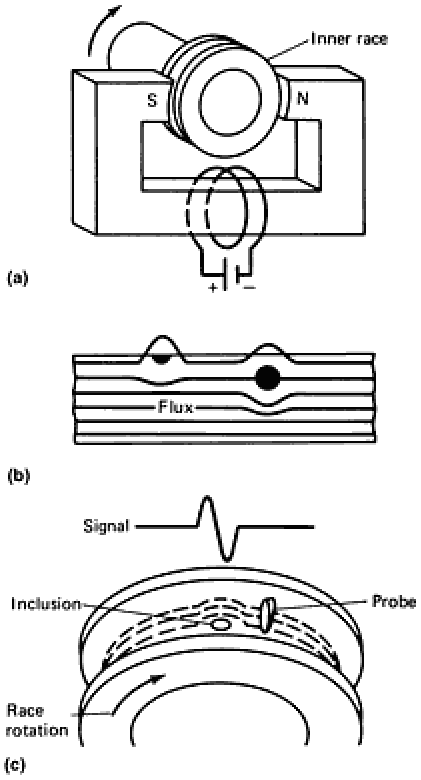


Fig. 5 Flux leakage inspection of a bearing race. (a) Magnetization of inner race. (b) Perturbation in the magnetic flux at the surface of the inner race. (c) Probe scanning the surface

The flux leakage method also is used to inspect steel reinforcement in concrete beams. The basic function of the magnetic field disturbance (MFD) inspection equipment is to provide maps of the magnetic field across the bottom and sides of the beam. An electromagnet on an inspection cart, which is suspended on tracks below the beam, provides a magnetic field that induces magnetization in permeable structures in its vicinity, such as steel rebars, cables, and stirrups. An array of Hall effect sensors distributed across the bottom and sides of the beam measures the field produced by magnetized structures within the beam. If a flaw is present in one of these magnetized structures, it produces a disturbance of the normal magnetic field pattern associated with the unflawed beam.

A flaw, such as a broken wire in a cable or a fractured rebar, produces a distinctive magnetic field anomaly that depends on the size of the discontinuity and its distance from the sensor. Because the signal shape that results from such an anomaly is known, flaw detection is enhanced by searching magnetic field records for specific signal shapes; that is, those that are characteristic of discontinuities in magnetic materials. In the MFD system, this is accomplished by a computer program that compares signal shapes with typical flaw signal shapes.

Nondestructive Characterization of Materials. Two examples of magnetic methods for monitoring material properties illustrate the types of tests that can be used. Measurements of magnetic characteristics provide data that yield information on different material properties. For example, different features of magnetic hysteresis data can be interpreted in terms of heat treatment and microstructure, plastic deformation, residual stress, and mechanical hardness.

An example of the effects of mechanical hardness on hysteresis data is shown in Fig. 6. These data were obtained in the absence of applied tensile stress. Specimens of different hardness were prepared by tempering at different temperatures. The grain size (ASTM No. 7) was the same for all four specimens used in the tests. Other data show that grain size has little effect on hysteretic behavior for the classes of alloys studied.

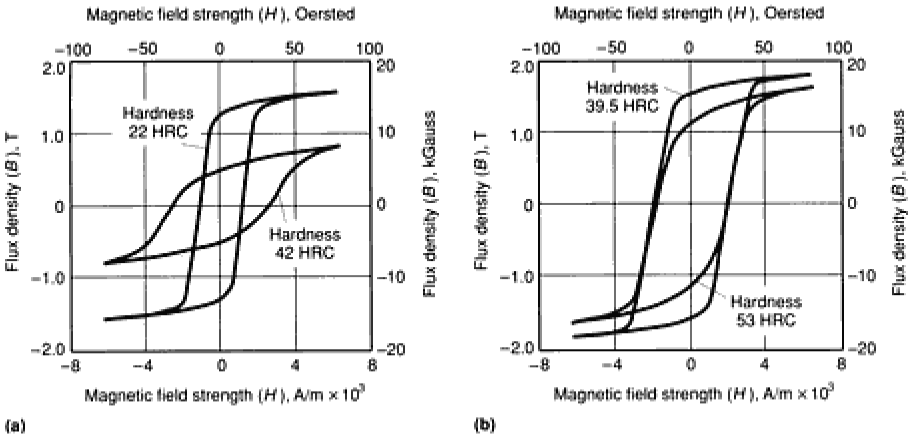


Fig. 6 Effect of mechanical hardness on hysteresis loop data. (a) AISI 410 stainless steel. (b) SAE 4340 steel

The main point illustrated in Fig. 6 is that the mechanically harder specimens of the same alloy are also harder to magnetize; that is, the flux density, *B*, obtained at a large value of *H* is smaller for mechanically harder specimens than for softer specimens. For one alloy, AISI 410 stainless steel, the hysteresis loop intersects the $B = 0$ axis at larger values of *H* for the harder specimen than for the softer specimen; that is, the coercive force is greater for the harder material. However, for SAE 4340 steel, the coercive force does not change with hardness. This suggests that, for these two alloys, the saturation flux density provides a more reliable measure of hardness than the coercive force.

Certain features of both Barkhausen noise and incremental permeability data can be correlated with depth of decarburization. The Barkhausen noise method shows a somewhat stronger sensitivity to depth, but is useful over a smaller range of depths than the incremental permeability method. It can be concluded that both methods are useful. The optimum choice of methods depends on the accuracy required and the expected depth of decarburization.

Eddy-Current Inspection

Introduction

EDDY-CURRENT INSPECTION is based on the principles of electromagnetic induction and is used to identify or differentiate a wide variety of physical, structural, and metallurgical conditions in electrically conductive ferromagnetic and nonferromagnetic metals and metal parts. Eddy-current inspection is used:

- To measure and identify conditions and properties related to electrical conductivity, magnetic permeability, and physical dimensions (primary factors affecting eddy-current response)
- To detect seams, laps, cracks, voids, and inclusions
- To sort dissimilar metals and detect differences in their composition, microstructure, and other properties (such as grain size, heat treatment, and hardness)
- To measure the thickness of a nonconductive coating on a conductive metal, or the thickness of a nonmagnetic metal coating on a magnetic metal

Because eddy-current inspection is an electromagnetic-induction technique, it does not require direct electrical contact with the part being inspected. The eddy-current method is adaptable to high-speed inspection, and because it is nondestructive, it can be used to inspect an entire production output if desired. The method is based on indirect measurement, and the correlation between instrument readings and the structural characteristics and serviceability of parts being inspected must be carefully and repeatedly established.

Eddy-current inspection is extremely versatile, which is both an advantage and a disadvantage. The advantage is that the method can be applied to many inspection problems provided that the physical requirements of the material are compatible with the inspection method. However, in many applications, the sensitivity of the method to many inherent material properties and characteristics can be a disadvantage. Some variables in a material that are not important in terms of material or part serviceability can cause instrument signals that mask critical variables or are mistakenly interpreted to be caused by critical variables.

Eddy-Current vs. Magnetic Inspection Methods. In eddy-current inspection, eddy currents create their own electromagnetic field, which is sensed either through the effects of the field on the primary exciting coil or by means of an independent sensor. In nonferromagnetic materials, the secondary electromagnetic field is derived exclusively from eddy currents. However, with ferromagnetic materials, additional magnetic effects occur that usually are of sufficient magnitude to overshadow the basic eddy-current effects from electrical conductivity only. These magnetic effects result from the magnetic permeability of the material being inspected, and can be virtually eliminated by magnetizing the material to saturation in a static (direct-current) magnetic field. When the permeability effect is not eliminated, the inspection method is more correctly categorized as electromagnetic or magnetoinductive inspection.

Principles of Operation

Functions of a Basic System. The part to be inspected is placed within or adjacent to an electrical coil in which an alternating current is flowing. As shown in Fig. 1, the alternating current, called the exciting current, causes eddy currents to flow in the part as a result of electromagnetic induction. These currents flow within closed loops in the part, and their magnitude and timing (or phase) depend on (a) the original or primary field established by the exciting currents, (b) the electrical properties of the part, and (c) the electromagnetic fields established by currents flowing within the part.

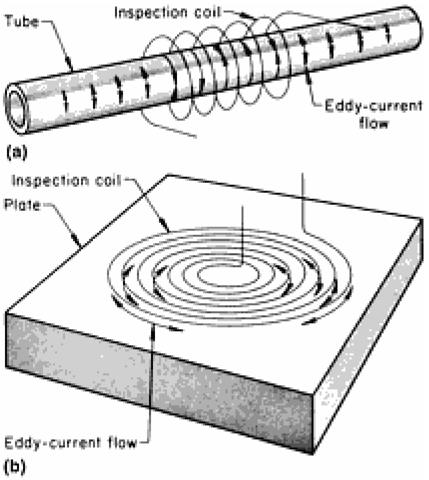


Fig. 1 Two common types of inspection coils and the patterns of eddy-current flow generated by the exciting current in the coils. Solenoid-type coil is applied to cylindrical or tubular parts; pancake-type coil, to a flat surface. (a) Solenoid-type coil. (b) Pancake-type coil

The electromagnetic field in the region in the part and surrounding the part depends on both the exciting current from the coil and the eddy currents flowing in the part. The flow of eddy currents in the part depends on the electrical characteristics of the part, the presence or absence of flaws and other discontinuities in the part, and the total electromagnetic field within the part.

The change in flow of eddy currents caused by the presence of a crack in a pipe is shown in Fig. 2. The pipe travels along the length of the inspection coil, as shown. In section A-A in Fig. 2, no crack is present and the eddy-current flow is symmetrical. In section B-B, where a crack is present, the eddy-current flow is impeded and changed in direction, causing significant changes in the associated electromagnetic field. The condition of the part can be monitored by observing the effect of the resulting field on the electrical characteristics of the exciting coil, such as its electrical impedance, induced voltage, and induced currents. Alternatively, the effect of the electromagnetic field can be monitored by observing the induced voltage in one or more other coils placed within the field near the part being monitored.

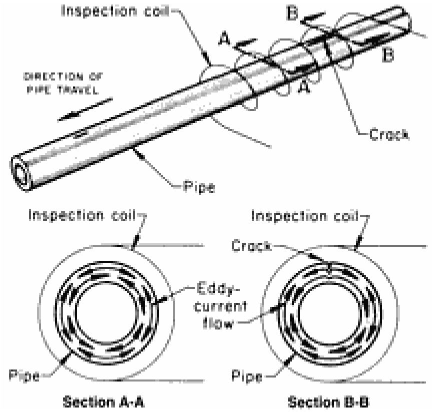

Inspection coil
B
A
B
A
DIRECTION OF PIPE TRAVEL
Crack
Pipe
Inspection coil
Inspection coil
Crack
Eddy-current flow
Pipe
Pipe
Section A-A
Section B-B

Fig. 2 Effect of a crack on the pattern of eddy-current flow in a pipe

Each and all of these changes can have an effect on the exciting coil and other coil or coils used to sense the electromagnetic field adjacent to a part. The effects most often used to monitor the condition of the part being inspected are the electrical impedance of the coil and the induced voltage of either the exciting coil or other adjacent coil or coils.

Eddy-current systems vary in complexity depending on individual inspection requirements. However, most systems must provide for the following functions:

- Excitation of the inspection coil with one or more frequencies
- Modulation of the inspection-coil output signal by the part being inspected
- Processing of the inspection-coil signal prior to amplification
- Amplification of the inspection-coil signals
- Detection or demodulation of the inspection-coil signal, usually accompanied by some analysis or discrimination of signals, which can be performed by a computer
- Display of signals on an instrument such as a meter, an oscilloscope, an oscillograph, and a strip-chart recorder; or recording of signals on paper punch tape and magnetic tape
- Handling of the part being inspected and support of inspection-coil assembly

Elements of a typical inspection system are shown schematically in Fig. 3. The particular elements in Fig. 3 are for a system developed to inspect bar or tubing. The generator supplies excitation current to the inspection coil and a synchronizing signal to the phase shifter, which provides switching signals for the detector. The loading of the inspection coil by the part being inspected modulates the electromagnetic field of the coil. This causes changes in the amplitude and phase of the inspection-coil voltage output.

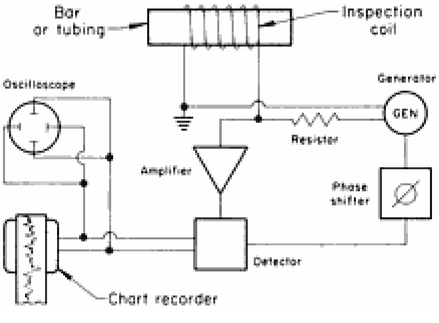

Bar or tubing
Inspection coil
Oscilloscope
Generator
GEN
Resistor
Amplifier
Phase shifter
Detector
Chart recorder

Fig. 3 Principal elements of a typical system for eddy current inspection of bar or tubing. See description in text.

The output of the inspection coil is fed to the amplifier and detected or demodulated by the detector. The demodulated output signal, after some further filtering and analyzing, is then displayed on an oscilloscope or a chart recorder. The displayed signals, having been detected or demodulated, vary at a much slower rate, depending on (a) the rate of changing the inspection probe from one part being inspected to another, (b) the speed at which the part is fed through an inspection coil, or (c) the speed with which the inspection coil is caused to scan past the part being inspected.

Operating Variables

The principal operating variables encountered in eddy-current inspection include coil impedance, electrical conductivity, magnetic permeability, lift-off and fill factors, edge effect, and skin effect.

Coil Impedance

When direct current flows in a coil, the magnetic field reaches a constant level and the electrical resistance of the wire is the only limitation to the flow of current. However, when alternating current flows in a coil, two limitations are imposed: the alternating-current resistance of the wire and a quantity known as inductive reactance (X_L).

Impedance usually is plotted on an impedance-plane diagram. In such a diagram, resistance is plotted along one axis and inductive reactance (or inductance) along the other axis. Because each specific condition in the material being inspected can result in a specific coil impedance, each condition corresponds to a particular point on the impedance-plane diagram. For example, if a coil is placed sequentially on a series of thick pieces of metal, each having a different resistivity, each piece causes a different coil impedance and corresponds to a different point on a locus in the impedance plane. The curve generated might resemble that shown in Fig. 4, which is based on International Annealed Copper Standard (IACS) conductivity ratings. Other curves are generated for other material variables, such as section thickness and types of surface flaws.

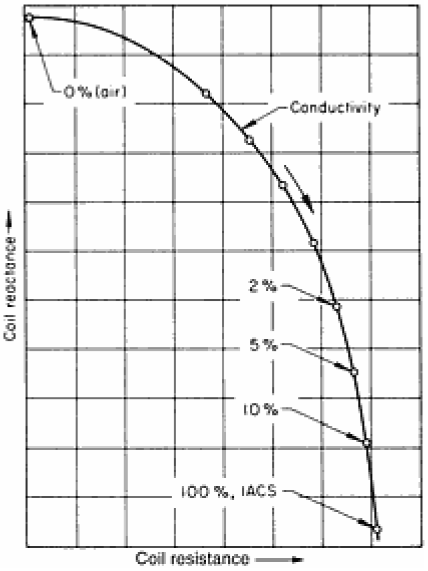


Fig. 4 Typical impedance-plane diagram derived by placing an inspection coil sequentially on a series of thick pieces of metal, each with a different International Annealed Copper Standard (IACS) electrical resistance or conductivity rating. The inspection frequency is 100 kHz.

By use of more than one test frequency, the impedance planes can be manipulated to accept a desirable variable (in flaws) and reduce the effects of undesirable variables--that is, lift-off and/or dimensional effects (see Fig. 3).

Electrical Conductivity

All materials have a characteristic resistance to the flow of electricity. Those with the highest resistivity are classified as insulators; those having intermediate resistivity are classified as semiconductors; and those having low resistivity are classified as conductors. Conductors, which include most metals, are of greatest interest in eddy-current inspection. The relative conductivities of common metals and alloys vary over a wide range.

Capacity to conduct current is measured in terms of either conductivity or resistivity. In eddy-current inspection, measurement often is based on IACS. In this system, the conductivity of annealed, unalloyed copper is arbitrarily rated at 100%, and the conductivities of other metals and alloys are expressed as percentages of this standard. Thus, the conductivity of unalloyed aluminum is rated 61% IACS, or 61% that of unalloyed copper. Table 1 gives the resistivities and IACS conductivity ratings of several common metals and alloys.

Table 1 Electrical resistivity and conductivity of several common metals and alloys

Metal or alloy	Resistivity $\mu\Omega\cdot$ mm	Conductivity, %IACS
Silver	16.3	105
Copper, annealed	17.2	100
Gold	24.4	70
Aluminum	28.2	61
Aluminum alloys		
6061-T6	41	42
7075-T6	53	32
2024-T4	52	30
Magnesium	46	37
70-30 brass	62	28
Phosphor bronzes	160	11
Monel	482	3.6
Zirconium	500	3.4
Zircaloy-2	720	2.4
Titanium	548	3.1
Ti-6Al-4V alloy	1720	1.0
Type 304 stainless steel	700	2.5
Inconel 600	980	1.7
Hastelloy X	1150	1.5
Waspaloy	1230	1.4

Magnetic Permeability

Ferromagnetic metals and alloys, including iron, nickel, cobalt, and some of their alloys, concentrate the flux of a magnetic field. They are strongly attracted to a magnet and an electromagnet, have exceedingly high and variable susceptibilities, and have very high and variable permeabilities.

Magnetic permeability is not a constant for a given material, but depends on the strength of the magnetic field acting on it. For example, consider a sample of steel that has been completely demagnetized and then placed in a solenoid coil. As current in the coil is increased, the magnetic field associated with the current increases. However, the magnetic flux within the steel increases rapidly at first and then levels off so that an additionally large increase in the strength of the magnetic field results in only a small increase in flux within the steel. The steel sample achieves a condition known as magnetic saturation.

The curve showing the relation between magnetic-field intensity and the magnetic flux within the steel is known as a magnetization curve. Magnetization curves for annealed commercially pure iron and nickel are shown in Fig. 5. The magnetic permeability of a material is the ratio between the strength of the magnetic field and the amount of magnetic flux within the material. As shown in Fig. 5, at saturation (where there is no appreciable change in induced flux in the material for a change in field strength) the permeability is nearly constant for small changes in field strength.

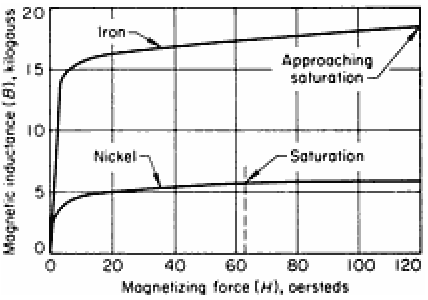


Fig. 5 Magnetization curves for annealed commercially pure iron and nickel

Magnetic permeability of the material being inspected strongly influences the eddy-current response. Consequently, the techniques and conditions used for inspecting magnetic materials differ from those used to inspect nonmagnetic materials.

"Lift-Off" Factor

When a probe inspection coil, attached to a suitable inspection instrument, is energized in air, it produces an indication even if there is no conductive material in the vicinity of the coil. The initial indication starts to change as the coil is moved closer to a conductor. Because the field of the coil is strongest close to the coil, the indicated change on the instrument continues to increase until the coil is directly on the conductor. These changes in indication with changes in spacing between the coil and the conductor, or part being inspected, are called "lift off." The lift-off effect is so pronounced that small variations in spacing can mask many indications resulting from the condition or conditions of primary interest. Consequently, it usually is necessary to maintain a constant relationship between the size and shape of the coil and the size and shape of the part being inspected.

The change of coil impedance with lift-off can be derived from the impedance-plane diagram shown in Fig. 6. When the coil is suspended in air away from the conductor, impedance is at a point at the upper end of the curve at far left in Fig. 6. As the coil approaches the conductor, the impedance moves in the direction indicated by the dashed lines until the coil is in contact with the conductor. When contact occurs, the impedance is at a point corresponding to the impedance of the part being inspected, which in this instance, represents its conductivity. The fact that the lift-off curves approach the conductivity curve at an angle can be used in some instruments to separate lift-off signals from those resulting from variations in conductivity or some other parameter of interest.

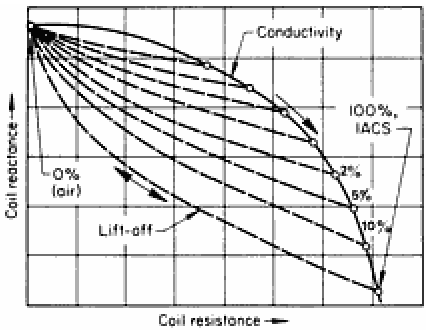


Fig. 6 Impedance-plane diagram showing curves for electrical conductivity and lift off. Inspection frequency is 100 kHz.

Although lift off can be troublesome in many applications, it can be also be useful. For example, using the lift-off effect, eddy current instruments are excellent for measuring the thickness of nonconductive coatings, such as paint and anodized coatings, on metals.

Fill Factor

In an encircling coil, a condition comparable to lift-off is known as "fill factor." It is a measure of how well the part being inspected fills the coil. As with lift off, changes in fill factor resulting from factors such as variations in outside diameter must be controlled because small changes can produce large indications. The lift-off curves shown in Fig. 6 are very similar to those for changes in fill factor. For a given lift-off or fill factor, the conductivity curve shifts to a new position, as indicated in Fig. 6. Fill factor can sometimes be used as a rapid method to check variations in outside-diameter measurements in rods and bars.

Edge Effect

When an inspection coil approaches the end or edge of a part being inspected, eddy currents are distorted because they are unable to flow beyond the edge of a part. The distortion of eddy currents results in an indication known as "edge effect." Because the magnitude of the effect is very large, it limits inspection near edges. Unlike lift-off, little can be done to eliminate edge effect. A reduction in coil size lowers the effect somewhat, but there are practical limits that dictate the sizes of coils for given applications. In general, it is not advisable to inspect any closer than 3.2 mm ($\frac{1}{8}$ in.) from the edge of a part.

One alternative for inspection near an edge with minimal edge effect is to scan in a line parallel to the edge. Inspection can be carried out by maintaining a constant probe-to-edge relationship, but each new scan-line position requires adjustment of the instrument. Fixturing of the probe is recommended.

Skin Effect

Eddy currents are not uniformly distributed throughout a part being inspected; rather, they are densest at the surface immediately beneath the coil and become progressively less dense with increasing distance below the surface. The concentration of eddy currents at the surface of a part is known as "skin effect." At some distance below the surface of a thick part, there essentially are no currents flowing. The depth of eddy-current penetration should be considered for thickness measurements and for detection of subsurface flaws.

Figure 7 shows how the eddy current varies as a function of depth below the surface. The depth at which the density of the eddy current is reduced to about 37% of the density at the surface is defined as the standard depth of penetration. This depth depends on the electrical conductivity and magnetic permeability of the material and on the frequency of the magnetizing current. Depth of penetration decreases with increases in conductivity, permeability, and inspection frequency. The standard depth of penetration can be calculated from the equation:

$$S = 1980\sqrt{\rho/\mu f}$$

where S is standard depth of penetration, in inches; ρ is resistivity, in ohm-centimeters; μ is magnetic permeability (1 for nonmagnetic materials); and f is inspection frequency, in hertz. Figure 8 shows the standard depth of penetration, as a function of inspection frequency, for several metals of various electrical conductivities.

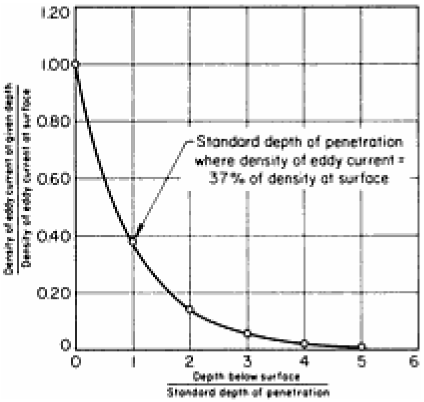


Fig. 7 Variation in density of eddy current as a function of depth below the surface of a conductor, known as

skin effect

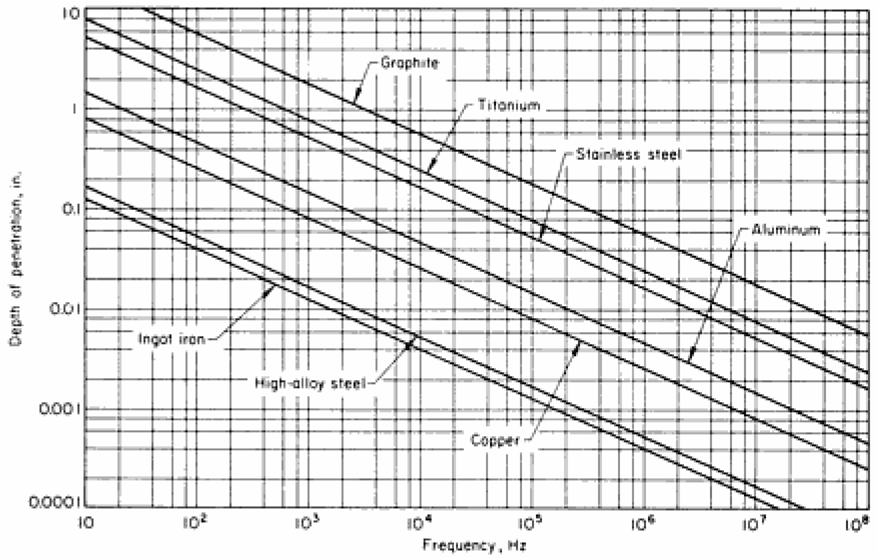


Fig. 8 Standard depths of penetration as a function of frequencies used in eddy-current inspection for several metals of various electrical conductivities

Inspection Frequencies

The inspection frequencies used in eddy-current inspection range from about 60 Hz to 6 MHz. Most inspection of nonmagnetic materials is performed at a few kilohertz. In general, lower frequencies are used to inspect magnetic materials. However, the actual frequency used in any specific eddy-current inspection depends on the thickness of the material being inspected, the required depth of penetration, the degree of sensitivity or resolution required, and the purpose of the inspection.

Selection of inspection frequency normally is a compromise. For example, penetration should be sufficient to reach subsurface flaws that must be detected, and to determine material condition (such as case hardness). Although penetration is greater at lower frequencies, it does not follow that the lowest possible frequency should be used. Unfortunately, as the frequency is lowered, the sensitivity to flaws decreases somewhat and the speed of inspection could be reduced.

Typically, the highest possible inspection frequency that still is compatible with the penetration depth required is selected. The choice is relatively simple when only surface flaws must be detected, in which case frequencies up to several megahertz can be used. However, when flaws at some considerable depth below the surface must be detected, or when flaw depth and size must be determined, low frequencies must be used at the expense of sensitivity.

In inspection of ferromagnetic materials, relatively low frequencies typically are used because of the low penetration in these materials. Higher frequencies can be used when it is necessary to inspect for surface conditions only. However, even the higher frequencies used in these applications still are considerably lower than those used to inspect nonmagnetic materials for similar conditions.

Inspection Coils

The inspection coil is an essential part of every eddy-current inspection system. The shape of the inspection coil depends to a considerable extent on the purpose of the inspection and on the shape of the part being inspected. In inspection for flaws, such as cracks and seams, it is essential that the flow of the eddy currents be as nearly perpendicular to the flaws as possible to obtain a maximum response from the flaws. If the eddy-current flow is parallel to flaws, there is little or no distortion of the currents, and, therefore, very little reaction on the inspection coil.

Probe and Encircling Coils. Of the almost infinite variety of coils used in eddy-current inspection, probe coils and encircling coils are the most common. A probe-type coil typically is used to inspect a flat surface for cracks at an angle to the surface because this type of coil induces currents that flow parallel to the surface, and therefore across a crack as shown in Fig. 9(a). Conversely, a probe-type coil is not suitable to detect a laminar type of flaw. For such a discontinuity, a U-shape, or horseshoe-shaped coil such as the coil shown in Fig. 9(b) is satisfactory.

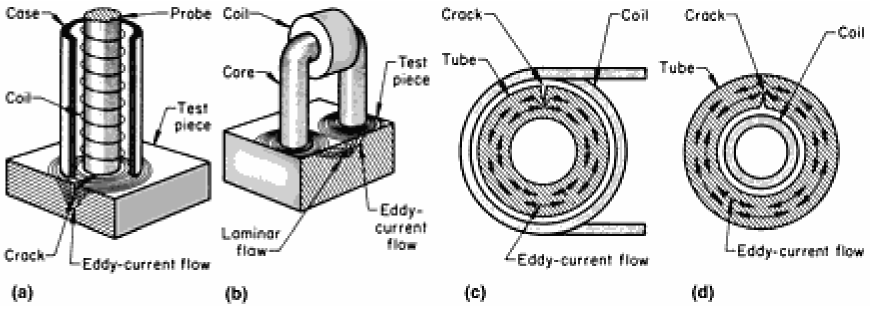


Fig. 9 Types and applications of coils used in eddy-current inspection. (a) Probe-type coil applied to a flat plate for crack detection. (b) Horseshoe-shape, or U-shape, coil applied to a flat plate for laminar-flaw detection. (c) Encircling coil applied to a tube. (d) Internal, or bobbin-type, coil applied to a tube

To inspect tubing and bar, an encircling coil (Fig. 9c) generally is used because of complementary configuration and because of the testing speeds that can be achieved. However, an encircling coil is sensitive only to discontinuities that are parallel to the axis of the tube and bar. The coil is satisfactory for this particular application because most discontinuities in tubing and bar are parallel to the major axis as a result of the manufacturing process. If it is necessary to locate discontinuities that are not parallel to the axis, a probe coil must be used, and either the coil or the part must be rotated during scanning. To detect discontinuities on the inside surface of a tube, an internal, or bobbin-type, coil (Fig. 9d) can be used. An alternative is to use an encircling coil with a depth of penetration sufficient to detect flaws on the inside surface. The bobbin-type coil, similar to the encircling coil, is sensitive to discontinuities that are parallel to the axis of the tube or bar.

Multiple Coils. In many eddy-current inspection setups, two coils are used. The two coils typically are connected in a series-opposing arrangement so there is no output from the pair when their impedances are the same. Pairs of coils can be used in either an absolute or a differential arrangement (see Fig. 10). In the absolute arrangement (Fig. 10a), a sample of acceptable material is placed in one coil, and the other coil is used for inspection. In this manner, the coils compare an unknown against a standard, the differences between the two (if any) are indicated by a suitable instrument. Arrangements of this type commonly are used in sort applications. Fixtures are used to maintain a constant geometrical relationship between coil and part.

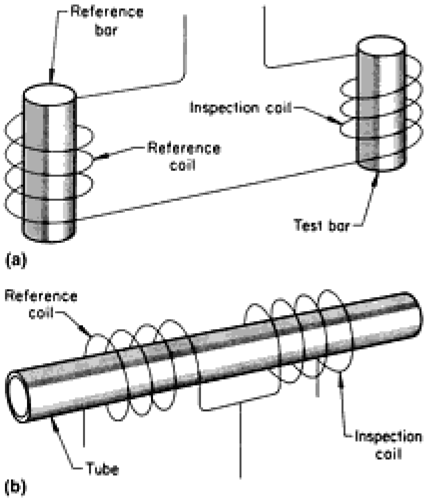


Fig. 10 Absolute and differential arrangements of multiple coils used in eddy-current inspection. (a) Absolute coil arrangement. (b) Differential coil arrangement

An absolute coil arrangement is not a good method in many applications. For example to inspect tubing, an absolute arrangement indicates dimensional variations in both outside diameter and wall thickness even though such variations can be well within allowable limits. To avoid this problem, a differential coil arrangement such as that shown in Fig. 10(b) can be used. Here, the two coils compare one section of the tube with an adjacent section. When the two sections are the same, there is no output from the pair of coils and no indication on the eddy-current instrument. Gradual dimensional variations within the tube or gross variations between individual tubes are not indicated, whereas discontinuities--which normally occur abruptly--are very apparent. In this way, it is possible to have an inspection system that is sensitive to flaws and relatively insensitive to changes that normally are not of interest.

Sizes and Shapes. Inspection coils are made in a variety of sizes and shapes. Selection of a coil for a particular application depends on the type of discontinuity. For example, when an encircling coil is used to inspect tubing and bar for short discontinuities, best resolution is obtained with a short coil. On the other hand, a short coil has the disadvantage of being sensitive to the position of the part in the coil. Longer coils are not as sensitive to position of the part, but are not as effective in detecting very small discontinuities. Small-diameter probe coils have greater resolution than larger ones but are more difficult to manipulate and are more sensitive to lift-off variations.

Eddy-Current Instruments

A simple eddy-current instrument, in which the voltage across an inspection coil is monitored, is shown in Fig. 11(a). This circuit is adequate to measure large lift-off variations, if accuracy is not of great importance. A circuit designed for greater accuracy is shown in Fig. 11(b). This instrument consists of a signal source, an impedance bridge with dropping resistors, an inspection coil in one leg, and a balancing impedance in the other leg. The differences in voltage between the two legs of the bridge are measured by an alternating-current voltmeter. Alternatively, the balancing impedance in the leg opposite the inspection coil can be a coil identical to the inspection coil, as shown in Fig. 11(c), or it can have a reference sample in the coil, as shown in Fig. 11(d). In the latter, if all the other components in the bridge are identical, a signal occurs only when the inspection-coil impedance deviates from that of the reference sample.

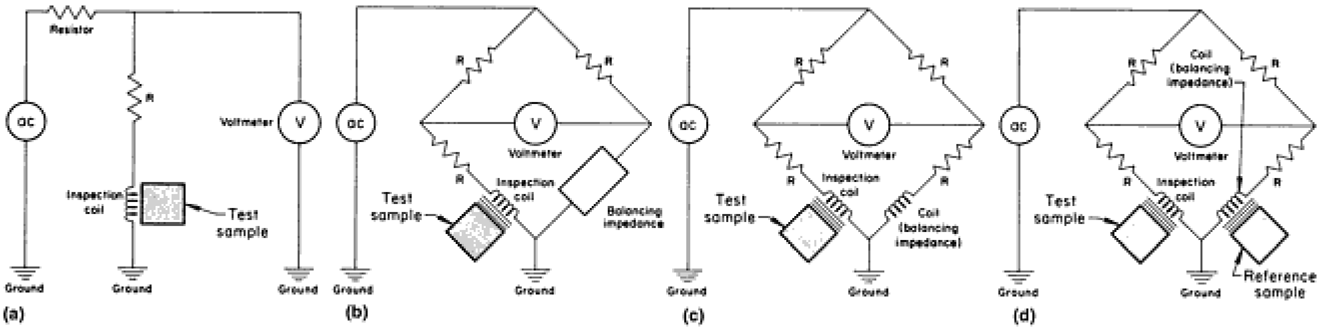
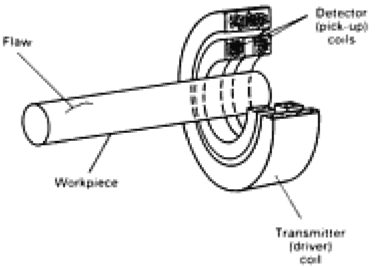


Fig. 11 Four types of eddy-current instruments. (a) A simple arrangement, in which voltage across the coil is monitored. (b) Typical impedance bridge. (c) Impedance bridge with dual coils. (d) Impedance bridge with dual coils and a reference sample in the second coil

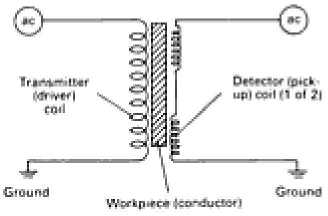
There are other methods to achieve bridge balance, such as varying the values of resistance of the resistor in the upper leg of the bridge and one in series with the balancing impedance. The most accurate bridges can measure absolute impedance to within 0.01%. However, in eddy-current inspection, it is not how an impedance bridge is balanced that is important, but rather how it is unbalanced by the effects of a flaw.

Another type of bridge system is an induction bridge, in which the power signal is transformer coupled into an inspection coil and a reference coil. In addition, the entire inductance-balance system is placed in the probe, as shown in Fig. 12. The probe consists of a large transmitter (or driver) coil and two small detector (or pickup) coils wound in opposite directions as mirror images of each other. An alternating current is supplied to the large transmitter coil to generate a magnetic field.

If the transmitter coil is not in the vicinity of a conductor, the two detector coils detect the same field, and the net signal is zero because they are wound in opposition to each other. However, if one end of the probe is placed near a metal surface, the field is different at the two ends of the probe, and a net voltage appears across the two coils. The resultant field is the sum of a transmitted signal, which is present all the time, and a reflected signal due to the presence of a conductor (the metal surface). This coil arrangement can be used both as a probe and as an encircling coil (see Fig. 12).



Arrangement of probe and workpiece



Wiring schematic for probe and workpiece

Fig. 12 Induction-bridge probe in place at the surface of a workpiece. Schematic shows how power signal is transformer coupled from a transmitter coil into two detector coils--an inspection coil (at bottom) and a reference coil (at top).

Readout Instrumentation. An important part of an eddy-current inspection system is the instrument used for a readout. The readout device can be an integral part of the system, an interchangeable plug-in module, and a solitary unit connected by cable. The readout instrument should be of adequate speed, accuracy, and range to meet the inspection requirements of the system. Frequently, several readout devices are used in a single inspection system. A list of more common types of readout, in order of increasing cost and complexity, follows:

- Alarm lights alert the operator that a test-parameter limit has been exceeded.
- Sound alarms serve the same purpose as alarm lights but free the attention of the operator to allow manipulating the probe in manual scanning.
- Kick-out relays activate a mechanism that automatically rejects and marks a part when a test parameter is exceeded.
- Analog meters give a continuous reading over an extended range. They are fairly rapid (with a frequency of about 1 Hz), and the scales can be calibrated to read parameters directly. The accuracy of these devices is limited to about 1% of full scale. They can be used to set the limits on alarm lights, sound alarms, and kick-out relays.
- Digital meters are easier to read and can have greater ranges than analog meters. Numerical values are easily read without extrapolation, but fast trends of changing readings are more difficult to interpret. Although many digital meters have binary coded decimal (bcd) output, they are relatively slow.
- X-Y plotters can be used to display impedance-plane plots of the eddy-current response. They are very helpful in the design and set up of eddy-current, bridge-unbalance inspections and in discriminating against undesirable variables. They also are useful to sort out inspection results. They are fairly accurate and provide a permanent copy.
- X-Y storage oscilloscopes are very similar to X-Y plotters but can acquire signals at high speed. However, the signals have to be processed manually, and the screen can quickly become cluttered with signals. In some instruments, high-speed X-Y gates can be displayed and set on the screen.
- Strip-chart recorders furnish a fairly accurate (about 1% of full scale) recording at reasonably high

speed (about 200 Hz). However, once on the chart, the data must be read by an operator. Several channels can be recorded simultaneously, and the record is permanent.

- Magnetic-tape recorders are fairly accurate and capable of recording at very high speed (10 MHz). Moreover, the data can be processed by automated techniques.
- Computers. The data from several channels can be fed directly to a high-speed computer, either analog or digital, for on-line processing. The computer can separate parameters and calculate the variable of interest and significance, catalog the data, print summaries of the result, and store all data on tape for reference in future scans.

Discontinuities Detectable by Eddy-Current Inspection

Basically, any discontinuity that appreciably alters the normal flow of eddy currents can be detected by eddy-current inspection. With encircling-coil inspection of either solid cylinders or tubes, surface discontinuities having a combination of predominantly longitudinal and radial dimensional components are readily detected. When discontinuities of the same size are located beneath the surface of the part being inspected at progressively greater depths, they become increasingly difficult to detect, and can be detected at depths greater than 13 mm ($\frac{1}{2}$ in.) only with special equipment designed for this purpose.

Conversely, laminar discontinuities such as those in welded tubes might not alter the flow of the eddy currents enough to be detected unless the discontinuity breaks either the outside or inside surfaces, or unless it produces a discontinuity in the weld from upturned fibers caused by extrusion during welding. A similar difficulty could arise in trying to detect a thin planar discontinuity that is oriented substantially perpendicular to the axis of the cylinder.

Regardless of the limitations, a majority of objectionable discontinuities can be detected by eddy-current inspection at high speed and at low cost. Some of the discontinuities that are readily detected are seams, laps, cracks, slivers, scabs, pits, slugs, open welds, miswelds, misaligned welds, black and gray oxide weld penetrators, pinholes, hook cracks, and surface cracks.

Reference Samples. A basic requirement for eddy-current inspection is a reliable, consistent means to set tester sensitivity to the proper level each time it is used. A standard reference sample must be provided for this purpose. Without this capability, eddy-current inspection is of little value. In selecting a standard reference sample, the usual procedure is to select a sample of product that can be run through the inspection system without producing appreciable indications from the tester. Several samples might have to be run before a suitable one is found; the suitable one then has reference discontinuities fabricated into it.

The type of reference discontinuities that must be used for a particular application are specified (for example, by ASTM and API). In selecting reference discontinuities, some of the major considerations are: (a) they must meet the required specification, (b) they should be easy to fabricate, (c) they should be reproducible, (d) they should be producible in precisely graduated sizes, and (e) they should produce an indication on the eddy-current tester that closely resembles those produced by the natural discontinuities.

Figure 13 shows several discontinuities that have been used for reference standards, these include a filed transverse notch, milled or electrical discharge machined longitudinal and transverse notches, and drilled holes.

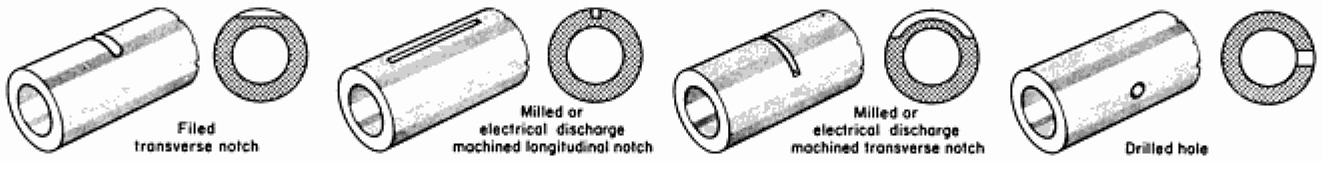

Filed transverse notch
Milled or electrical discharge machined longitudinal notch
Milled or electrical discharge machined transverse notch
Drilled hole

Fig. 13 Several fabricated discontinuities used as reference standards in eddy-current inspection. ASTM standards for eddy-current testing include E 215 (aluminum alloy tube), E 376 (measurement of coating thickness), E 243 (copper and copper alloy tube), E 566 (ferrous metal sorting), E 571 (nickel and nickel alloy

tube), E 690 (nonmagnetic heat-exchanger tubes), E 426 (stainless steel tube), and E 309 (steel tube).

Microwave Inspection

Introduction

MICROWAVES (or radar waves) are a form of electromagnetic radiation with wavelengths between 1000 cm and 1 mm in free space. Because microwaves have wavelengths that are 10^4 to 10^5 times longer than those of light waves, microwaves penetrate deeply into materials, with the depth of penetration dependent on the conductivity, permittivity, and permeability of the materials. Microwaves are also reflected from any internal boundaries and interact with the molecules that constitute the material. For example, it was found that the best source for the thickness and voids in radomes was the microwaves generated within the radomes. Both continuous and pulsed incident waves were used in these tests, and either reflected or transmitted waves were measured.

One of the first important uses of microwaves in nondestructive evaluation (NDE) was for components such as waveguides, attenuators, cavities, antennas, and antenna covers (radomes). Subsequently, microwave inspection methods were developed for:

- Evaluation of moisture content in dielectric materials
- Thickness measurements of thin metallic coatings on dielectric substrates
- Detection of voids, delaminatrons, macroporosity, inclusions, and other flaws in plastic or ceramic materials.

Advantages

In comparison with ultrasonic inspection and x-ray radiographic inspection, the advantages of inspection with microwaves are as follows:

- Broadband frequency response of the coupling antennas
- Efficient coupling through air from the antennas to the material
- No material contamination problem caused by the coupling
- Microwaves readily propagate through air, so successive reflections are not obscured by the first one.
- Information concerning the amplitude and phase of propagating microwaves is readily obtainable.
- No physical contact is required between the measuring device and the material being measured; therefore, the surface can be surveyed rapidly without contact.
- The surface can be scanned in strips merely by moving the surface or by scanning the surface with antennas.
- No changes are caused in the material; therefore, the measurement is nondestructive.
- The complete microwave system can be made from solid-state components so that it will be small, rugged, and reliable.
- Microwaves can be used for locating and sizing cracks in materials if the following considerations are followed. First, the skin depth at microwave frequencies is very small (a few micrometers), and the crack is detected most sensitively when the crack breaks through the surface. Second, when the crack is not through the surface, the position of the crack is indicated by a detection of the high stresses in the surface right about the subsurface crack. Finally, microwave crack detection is very sensitive to crack opening and to the frequency used. Higher frequencies are needed for the smaller cracks. If the frequency is increased sufficiently, the incident wave can propagate into the crack, and the response is then sensitive to crack depth.

Limitations

The use of microwaves is in some cases limited by their inability to penetrate deeply into conductors or metals. This means that nonmetallic materials inside a metallic container cannot be easily inspected through the container. Another limitation of the lower-frequency microwaves is their comparatively low power for resolving localized flaws. If a receiving antenna of practical size is used, a flaw with effective dimension that is significantly smaller than the wavelength of the microwaves used cannot be completely resolved (that is, distinguished as a separate, distinct flaw). The shortest wavelengths for which practical present-day microwave apparatus exists are of the order of 1 mm (0.04 in.). However, the development of microwave sources with wavelengths of 0.1 mm (0.004 in.) are proceeding rapidly. Consequently, microwave inspection for the detection of very small flaws is not suited for applications in which flaws are equal to or smaller than 0.1 mm (0.004 in.). Subsurface cracks can be detected by measuring the surface stress, which should be much higher in the surface above the subsurface crack.

Techniques of Microwave Inspection

The following general approaches have been used in the development of microwave nondestructive inspection:

- Fixed-frequency, continuous-wave transmission
- Swept-frequency, continuous-wave transmission
- Pulse-modulated transmission
- Fixed-frequency, continuous-wave reflection
- Swept-frequency, continuous-wave reflection
- Pulse-modulated reflection
- Fixed-frequency standing waves
- Fixed-frequency reflection scattering
- Microwave holography
- Microwave surface impedance
- Microwave detection of stress corrosion

Each of these techniques uses one or more of the several processes by which materials can interact with microwaves, namely, reflection, refraction, scattering, absorption, and dispersion. The basic components of the transmission technique are shown schematically in Fig. 1.

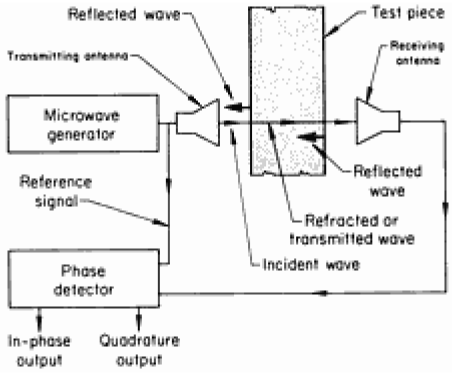


Fig. 1 Diagram of the basic components of the transmission technique used for microwave inspection

Thickness measurements

Thickness measurements can be made with microwave techniques on both metallic and nonmetallic materials. For metals, two reflected waves are used from two waveguide arms that differ in length by an integral number of half-wavelengths for detector output null. This measurement is made using the standing wave technique. When the wave is incident on a metal (electrically conductive), most of the wave is reflected; only a small amount is transmitted (refracted). The transmitted wave is highly attenuated in the metal within the first skin depth. For nonmetallic materials (electrically nonconductive), the reflected wave is much smaller than the incident wave, so that any standing wave that does develop does not have a large amplitude.

Detection of Discontinuities

Discontinuities such as cracks, voids, delaminations, separations, and inclusions predominantly reflect or scatter electromagnetic waves. Wherever these types of flaws occur, there is a more or less sharp boundary between two materials having markedly different velocities for electromagnetic waves. At these boundaries, which are usually thin compared to the wavelength of electromagnetic radiation being used, the electromagnetic wave is reflected, refracted, or scattered. The reflected or scattered radiation has appreciable amplitude only if the minimum dimension of the discontinuity is larger than about one-half the wavelength of the incident radiation in the material being tested.

Porosity and regions of defective material such as departures from nominal composition do not produce strong reflection or scattering. They do influence the attenuation and the velocity of the electromagnetic wave. When there is absorption, the transmitted wave has an exponential decay with respect to the distance traveled.

Microwave Detection of Surface Cracks in Metals

When an electromagnetic wave is incident on a metallic surface that has slits or cracks, the metallic surface reradiates (reflects) a signal because of induced current. Under the proper conditions, the reflected wave combines with the incident wave to produce a standing wave. The reflection from a surface without a crack is different from that surface with a crack and depends on the direction of the incident wave polarization relative to the crack. When the crack is long and narrow and the electric field is perpendicular to the length of the crack, the reflected wave (and therefore any standing wave) is affected by the presence of the crack. The amount of change is used to determine the size and depth of the crack.

Ultrasonic Inspection

Introduction

ULTRASONIC INSPECTION is a nondestructive method in which beams of high-frequency acoustic energy are introduced into a material to detect surface and subsurface flaws, to measure the thickness of the material, and to measure the distance to a flaw. An ultrasonic beam travels through a material until it strikes an interface or discontinuity such as a flaw. Interfaces and flaws interrupt the beam and reflect a portion of the incident acoustic energy. The amount of energy reflected is a function of (a) the nature and orientation of the interface or flaw and (b) the acoustic impedance of such a reflector. Energy reflected from various interfaces and flaws can be used to define the presence and locations of flaws, the thickness of the material, and the depth of a flaw beneath a surface.

Most ultrasonic inspections are performed using a frequency between 1 and 25 MHz. Short shock bursts of ultrasonic energy are aimed into the material from the ultrasonic search unit of the ultrasonic flaw-detector instrument. The electrical pulse from the flaw detector is converted into ultrasonic energy by a piezoelectric transducer element in the search unit. The beam pattern from the search unit is determined by the operating frequency and size of the transducer element. Ultrasonic energy travels through the material at a specific velocity that is dependent on the physical properties of the material and on the mode of propagation of the ultrasonic wave. The amount of energy reflected from or transmitted through an interface, other type of discontinuity, or reflector is dependent on the properties of the reflector. These phenomena provide the basis for establishing two of the most common measurement parameters used in ultrasonic inspection: the amplitude of the energy reflected from an interface or flaw and the time required (from pulse initiation) for the ultrasonic beam to reach the interface or flaw.

Ultrasonic Flaw Detectors

Although the electronic equipment used for ultrasonic inspection can vary greatly in detail among equipment manufacturers, all general-purpose units consist of a power supply, a pulser circuit, a search unit, a receiver-amplifier circuit, an oscilloscope, and an electronic clock. Many systems also include electronic equipment for signal conditioning, gating, automatic interpretation, and integration with a mechanical or electronic scanning system. Also, advances in microprocessor technology have extended the data acquisition and signal-processing capabilities of ultrasonic inspection systems. In most instances the entire electronic assembly, including the controls and display, is contained in a single instrument. A typical ultrasonic flaw detector is shown in Fig. 1. The major controls include:

- Frequency selector to select the operating or test frequency
- Pulse-tuning control to fine adjust the test frequency
- Pulse-repetition-rate control, which determines the number of times per second that an ultrasonic pulse is initiated from the transducer (typically 100 to 2000 pulses per second)
- Test-type or mode-selection switch to adjust instrument to pulse-echo or pitch-catch operation
- Sensitivity controls to adjust sensitivity or gain of the receiver-amplifier
- Sweep selector and delay to adjust time base and that portion of the inspection zone that is to be displayed
- Gate-position control to isolate the portion of the inspection zone that will be used for additional processing
- Oscilloscope, which provides the visual display of the time and amplitude parameters used to interpret the data from the ultrasonic inspection

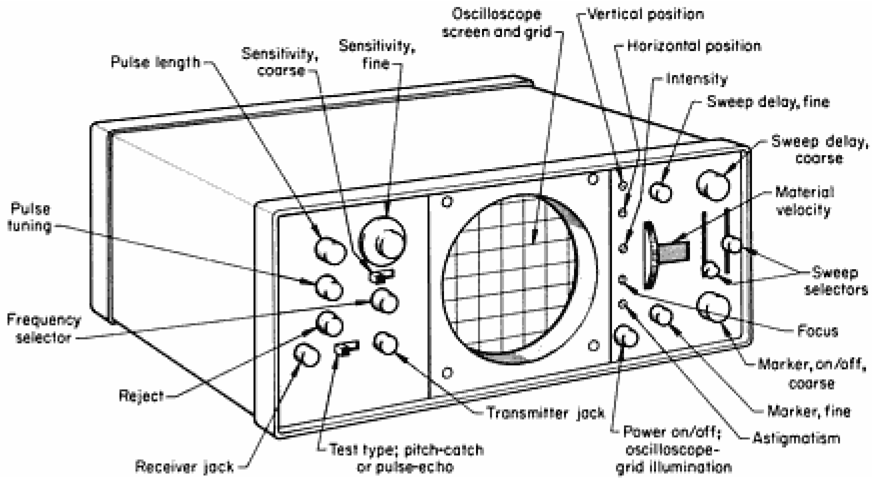

Oscilloscope screen and grid
Vertical position
Horizontal position
Intensity
Sweep delay, fine
Pulse length
Sensitivity, coarse
Sensitivity, fine
Sweep delay, coarse
Material velocity
Pulse tuning
Sweep selectors
Frequency selector
Focus
Marker, on/off, coarse
Reject
Marker, fine
Transmitter jack
Astigmatism
Power on/off; oscilloscope-grid illumination
Receiver jack
Test type; pitch-catch or pulse-echo

Fig. 1 Typical pulse-echo instrument

Ultrasonic Transducers and Search Units

Generation and detection of ultrasonic waves for inspection is accomplished by means of a transducer element. The transducer element is contained within a device most often referred to as a search unit (or sometimes as a probe). The active element in a search unit is a piezoelectric crystal. Piezoelectricity is pressure-induced electricity, a property characteristic of certain naturally occurring crystalline compounds and some man-made materials. An electrical charge is developed by the crystal when pressure is applied to it. Conversely, when an electrical field is applied, the crystal mechanically deforms (changes shape). Piezoelectric crystals have various deformation modes; thickness expansion is the principal mode used in transducers for ultrasonic inspection.

The most common types of piezoelectric materials used for ultrasonic search units are quartz; lithium sulfate; and polarized ceramics such as barium titanate, lead zirconate titanate, and lead metaniobate. Table 1 summarizes characteristics and applications of these materials.

Table 1 Characteristics and applications of piezoelectric transducer elements

Piezoelectric element	Characteristics of piezoelectric elements							Suitability of element in:		
	Efficiency				**Tolerance to elevated temperature**	**Damping ability**	**Undesired modes (inherent noise)**	**Contact inspection**		**Immersion inspection**
	Transmit	**Receive**	**Coupling**					**Straight-beam**	**Angle-beam**	
			To water	**To metal**						
Quartz	P	G	G	F	G	F	G	G	F	G
Lithium sulfate	F	E	E	P	P	E	E	P	F	E
Barium titanate	G	P	G	G	P	P	P	G	G	F
Lead zirconate titanate	E	F	F	E	E	F	P	E	E	F
Lead metaniobate	G	F	G	E	E	E	G	E	E	G

Search units come in a variety of types and shapes. Variations in search-unit construction include transducer-element material; transducer-element thickness, surface area, and shape; and type of backing material and degree of loading. Four basic types of search units are straight-beam contact, angle-beam contact, dual-element contact, and immersion, both flat and focused. Table 2 lists their primary areas of application. Sectional views of these search units, together with a special type (delay-tip, contact-type search unit), are shown in Fig. 2.

Table 2 Primary applications of ultrasonic search units

Straight-beam, contact-type units

- Manufacturing-induced flaws:
    - Billets--inclusions, stringers, pipe
    - Forgings--inclusions, cracks, segregations, seams, flakes, pipe
    - Rolled products--laminations, inclusions, tears, seams, cracks
    - Castings--slag, porosity, cold shuts, tears, shrinkage cracks, inclusions
- Service-induced flaws: fatigue cracks, corrosion, erosion, stress-corrosion cracks

Angle-beam, contact-type units

- Manufacturing-induced flaws:
    - Forgings--cracks, seams, laps
    - Rolled products--tears, seams, cracks, cupping
    - Welds--slag inclusions, porosity, incomplete fusion, incomplete penetration, dropthrough, suckback, cracks in filler metal and base metal
    - Tubing and pipe--circumferential and longitudinal cracks
- Service-induced flaws: fatigue cracks, stress-corrosion cracks

Dual-element, contact-type units

- Manufacturing-induced flaws:
    - Plate and sheet--thickness measurement, lamination detection
    - Tubing and pipe--measurement of wall thickness
- Service-induced flaws: wall thinning, corrosion, erosion, stress-corrosion cracks

Immersion-type units

- Manufacturing-induced flaws:
    - Billets--inclusions, stringers, pipe
    - Forgings--inclusions, cracks, segregations, seams, flakes, pipe
    - Rolled products--laminations, inclusions, tears, seams, cracks
    - Welds--inclusions, porosity, incomplete fusion, incomplete penetration, dropthrough, cracks, base-metal laminations
    - Adhesive-bonded, soldered, or brazed products--lack of bond
    - Composites--voids, resin rich, resin poor, lack of filaments
    - Tubing and pipe--circumferential and longitudinal cracks
- Service-induced flaws: corrosion, fatigue cracks

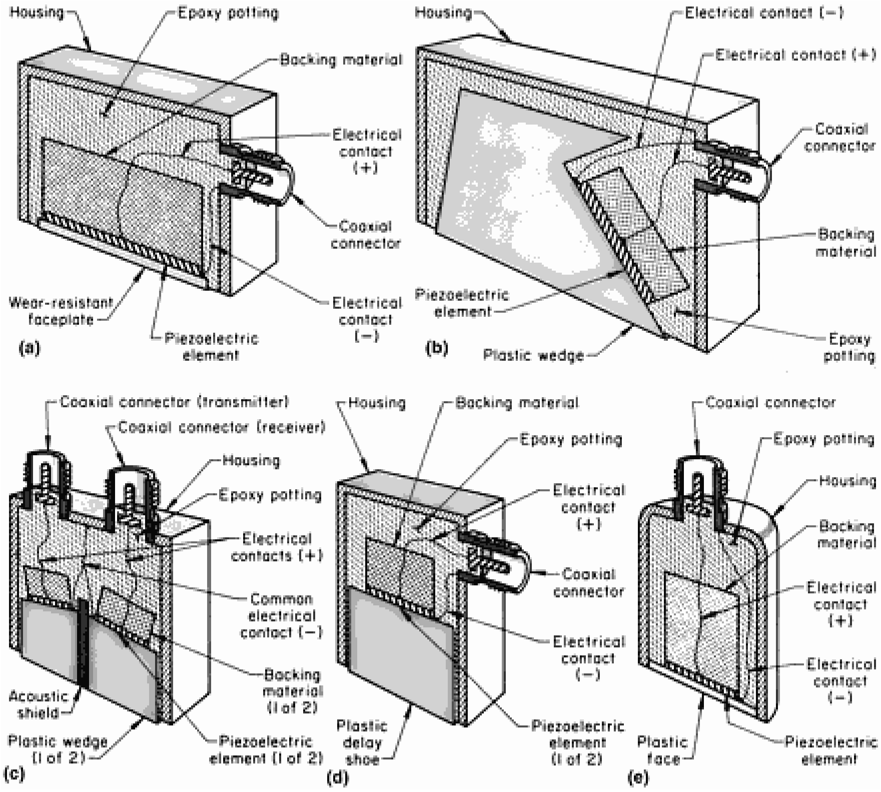

Housing
Epoxy potting
Backing material
Electrical contact (+)
Coaxial connector
Electrical contact (−)
Wear-resistant faceplate
Piezoelectric element
(a)
Housing
Electrical contact (−)
Electrical contact (+)
Coaxial connector
Backing material
Piezoelectric element
Epoxy potting
Plastic wedge
(b)
Coaxial connector (transmitter)
Coaxial connector (receiver)
Housing
Epoxy potting
Electrical contacts (+)
Common electrical contact (−)
Backing material (1 of 2)
Acoustic shield
Plastic wedge (1 of 2)
Piezoelectric element (1 of 2)
(c)
Housing
Backing material
Epoxy potting
Electrical contact (+)
Coaxial connector
Electrical contact (−)
Piezoelectric element (1 of 2)
Plastic delay shoe
(d)
Coaxial connector
Epoxy potting
Housing
Backing material
Electrical contact (+)
Electrical contact (−)
Piezoelectric element
Plastic face
(e)

Fig. 2 Sectional views of five types of search units used in ultrasonic inspection. (a) Straight-beam (longitudinal-wave) contact. (b) Angle-beam (shear-wave) contact. (c) Dual-element contact. (d) Delay-tip (stand-off) contact. (e) Immersion

The selection of a transducer depends very much on the properties of the test specimen, particularly its sound attenuation. Ultrasonics of high frequency produce good resolution, which is the ability to separate echoes from closely spaced defects. Ultrasonics of low frequency penetrate deeper into materials because attenuation is generally lower. However, backscattering "noise" from grain boundaries is usually more important than attenuation, although the net result is the same because the signal-to-noise ratio also usually decreases with frequency. This is shown in Fig. 3. This means that the two requirements of high penetration and high resolution are mutually exclusive. For example, a specimen having high attenuation, such as steel, should be examined by a low frequency beam of about 0.5 MHz and a large transducer diameter about 50 mm (2 in.), which provides a high penetration, but a relatively low lateral resolution of about 6 mm ($\frac{1}{4}$ in.). Improved resolution can be obtained by using shear waves, because these have shorter wavelengths than compression waves of the same frequency in the solid. (The velocity of a longitudinal wave in a solid is greater than that of the shear wave of the same frequency.) Large diameter transducers are chosen to produce a narrow focused beam, which enhances the lateral resolution.

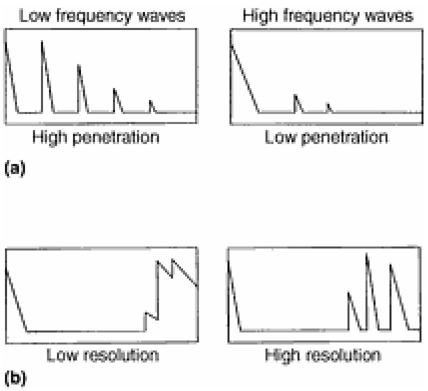


Fig. 3 Oscilloscope displays using ultrasonic transducers of (a) high and low penetration (ability to detect defects at distances within the solid), and (b) high and low resolution (ability to separate echoes from closely-spaced defects)

Couplants

Air is a poor transmitter of sound waves at megahertz frequencies. Also, because the acoustic impedance mismatch between air and most solids is significant, even a very thin layer of air severely retards the transmission of sound waves from the transducer to the test piece. Therefore, it is necessary to use a couplant to eliminate air between the transducer and the test piece for satisfactory contact inspection.

Couplants normally used for contact inspection include water, oils, glycerin, petroleum greases, silicone grease, cellulose gum, and various commercial pastelike substances. Certain soft rubbers that transmit sound waves can be used where adequate coupling can be achieved by applying pressure to the search unit.

Factors that should be considered in selecting a couplant include:

- Surface finish of test piece
- Temperature of test surface
- Possibility of chemical reactions between test surface and couplant
- Cleaning requirements (some couplants are difficult to remove)

Water is a suitable couplant for use on a relatively smooth surface, but a wetting agent should be added. The addition of glycerin sometimes is necessary to increase viscosity.

Heavy oil or grease should be used on hot and vertical surfaces and on rough surfaces where irregularities need to be filled.

Cellulose gum is especially useful on rough surfaces when good coupling is needed to minimize background noise and yield an adequate signal-to-noise ratio.

Basic Inspection Methods

Ultrasound can be used to measure material thickness by (a) determining resonant frequencies of a test piece and (b) measuring time required for an ultrasonic-wave packet (pulse) to traverse the test piece. The former uses reflected ultrasound to create standing waves in the test piece; the frequencies at which standing waves occur are used to compute thickness. In the latter method, the time it takes for a pulse of ultrasonic energy to be transmitted through the test piece is measured; this time period can be 100 nanoseconds or less. Thickness is calculated as the product of the measured time of flight and the known acoustic-wave velocity.

Ultrasound can be used to detect flaws by measuring (a) the amplitude of the acoustic pressure wave and time of flight of reflected acoustic waves and (b) the amplitude of the acoustic pressure wave of either transmitted or reflected acoustic waves. The pulse-echo technique is the most widely used ultrasonic technique. Flaws are detected and their sizes estimated by comparing the amplitude of a reflected echo from an interface (either within the test piece or at the back surface) with the amplitude of an echo reflected from a reference interface of known size or from the back surface of a test piece that has no flaws. The echo from the back surface (back reflection) serves as a reference point for time-of-flight measurements that enable measuring the depth of some internal flaws. It is necessary that an internal flaw reflect at least part of the sound energy onto the receiving transducer to measure depth. However, echoes from flaws are not essential to their detection. Just because the amplitude of an echo from back reflection of a test piece is lower than that of an echo from an identical flaw-free workpiece implies that the test piece contains one or more flaws. Detection of the presence of flaws by sound attenuation is used in both transmission and pulse-echo techniques. The inability to detect flaw depth is the main disadvantage of attenuation techniques.

Pulse-Echo Method

In pulse-echo inspection, short bursts of ultrasonic energy (pulses, or wave packets) are introduced into a test piece at regular time intervals. If the pulses encounter a reflecting surface, some or all of the energy is reflected. The proportion of energy that is reflected is highly dependent on the size of the reflecting surface in relation to the size of the incident ultrasonic beam. The direction of the reflected beam (echo) depends on the orientation of the reflecting surface with respect to the incident beam. Reflected energy is monitored; both the amount of energy reflected in a specific direction and the time delay between transmission of the initial pulse and receipt of the echo are measured.

Principles of Operation. Most pulse-echo systems consist of (a) an electronic clock; (b) an electronic signal generator, or pulser; (c) a sending transducer; (d) a receiving transducer; (e) an echo-signal amplifier; and (f) a display device. In the most widely used version of pulse-echo systems, a single transducer acts alternatively as a sending and receiving transducer. The clock and signal generator usually are combined in a signal electronic unit. Frequently, circuits that amplify and demodulate echo signals from the transducer are housed in the same unit.

In a pulse-echo system with a single search unit, the electronic clock triggers the signal generator at regular intervals, which imposes a short burst of high-frequency alternating voltage on the transducer element. Simultaneously, the clock activates a time-measuring circuit connected to the display device. The operator preselects a constant interval between pulses by means of a "pulse-repetition-rate" control on the instrument; pulses usually are repeated 100 to 2000 times per second. The operator also can preselect the signal generator or pulser output frequency. For best results, frequency (and sometimes the pulse-repetition rate) should be tuned to achieve the maximum response of the transducer (resonance in the vibrating element) and maximum signal-to-noise ratio (lowest amount of electronic noise) in the electronic equipment. The transducer converts the pulse of alternating voltage into a pulse of mechanical vibration having essentially the same frequency as the imposed alternating voltage. The mechanical vibration (ultrasound) is introduced into a test piece through a couplant and travels by wave motion through the test piece at the speed of sound. When the pulse of ultrasound encounters a reflecting surface that is perpendicular to the direction of travel, ultrasonic energy is reflected and returns to the transducer. The returning pulse travels along the same path and at the same speed as the initial pulse, but in the opposite direction.

Data Presentation. Information from pulse-echo inspection can be displayed in one of three forms: (a) A-scan, which is a quantitative display of echo amplitude and time-of-flight data obtained at a single point on the surface of the test piece; (b) B-scan, which is a quantitative cross-sectional display of time-of-flight data obtained along a plane perpendicular to the surface of the test piece; or (c) C-scan, which is a semiquantitative display of echo amplitude obtained over an area of the surface of the test piece. The A-scan display, which is the most widely used form, can be analyzed in terms of the type, size, and location (chiefly depth) of internal flaws.

A-scan display basically is a plot of amplitude versus time, in which a horizontal baseline on an oscilloscope screen indicates elapsed time and vertical deflections (called indications or signals) represent echos. A typical A-scan setup that illustrates the essential elements in a basic system for pulse-echo inspection is shown in Fig. 4. These elements include:

- Power supply, which can run on 110-volt alternating current or on batteries
- Electronic clock, or timing circuit, to trigger pulser and display circuits
- Pulser circuit, or rate generator, to control frequency, amplitude, and pulse-repetition rate of the voltage pulses that excite the search unit
- Receiver-amplifier circuit to convert output signals from the search unit into a form suitable for oscilloscope display
- Sweep circuit to control (a) time delay between search-unit excitation and start of oscilloscope trace and (b) rate at which oscilloscope trace travels horizontally across the screen
- Marker circuit (optional) to produce a secondary trace, on or below the main trace, usually in the form of a square wave, which is used for precise depth measurements
- Oscilloscope screen, including separate controls for trace brightness, trace focus, and illuminated measuring grid
- Flaw gate (not shown) to isolate the echo of interest for further processing

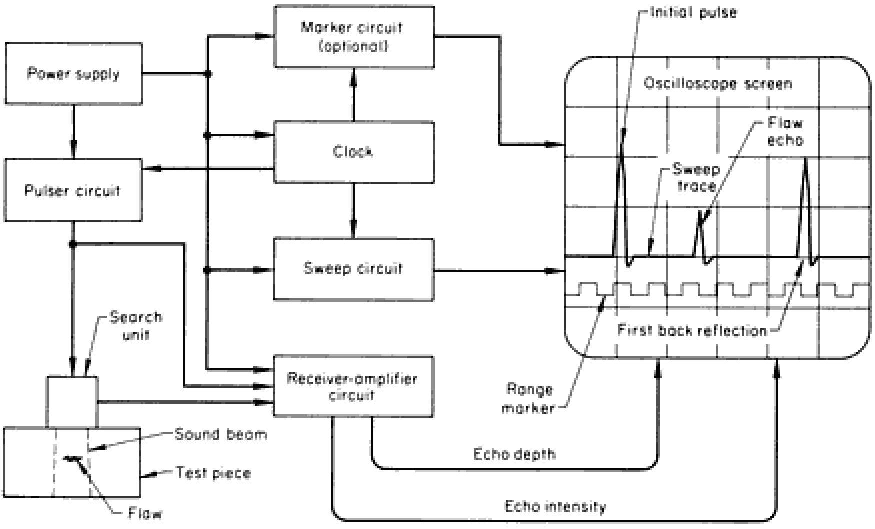


Fig. 4 Typical A-scan setup, including video-mode display, for a basic pulse-echo, ultrasonic-inspection system

The search unit and the coaxial cable connecting the unit to the instrument, although not strictly part of the electronic circuitry, must be matched to the electronics.

B-scan display is a plot of time versus distance, in which one orthogonal axis on the display corresponds to elapsed time, while the other axis represents the position of the search unit along a line on the surface of the test piece relative to the position of the search unit at the start of the inspection. Echo amplitude is not measured directly as in A-scan inspection, but often it is indicated semiquantitatively by the relative brightness of echo indications on an oscilloscope screen.

Figure 5 shows a typical B-scan system. System functions are identical to those of the A-scan system except for the following differences:

- The display is generated on an oscilloscope screen consisting of a long-persistence phosphor; that is, a phosphor that continues to fluoresce long after the means of excitation ceases to fall on the fluorescing area of the screen. This allows the imaginary cross section to be viewed as a whole without having to resort to permanent imaging methods such as photographs. (Photographic equipment, facsimile recorders, or *x-y* plotters can be used to record B-scan data for later reference.)

- Oscilloscope input for one axis of the display is provided by an electromechanical device, which generates an electrical voltage proportional to the position of the search unit relative to a reference point on the surface of the test piece. Most B-scans are generated by scanning the search unit in a straight line across the surface of the test piece at a uniform rate. One axis of the display (usually the horizontal axis) represents the distance traveled along this line.
- Echoes are indicated by bright spots on the screen rather than by deflections of the time trace. The position of a bright spot along the axis orthogonal to the search-unit position axis (usually measured top to bottom on the screen) indicates the depth of the echo within the test piece.
- The echo-intensity signal from the receiver-amplifier is connected to the trace-brightness control on the oscilloscope to ensure that echoes are recorded as bright spots. In some systems, the brightnesses corresponding to different values of echo amplitude has sufficient contrast to permit semiquantitative appraisal of echo amplitude, which is related to flaw size and shape.

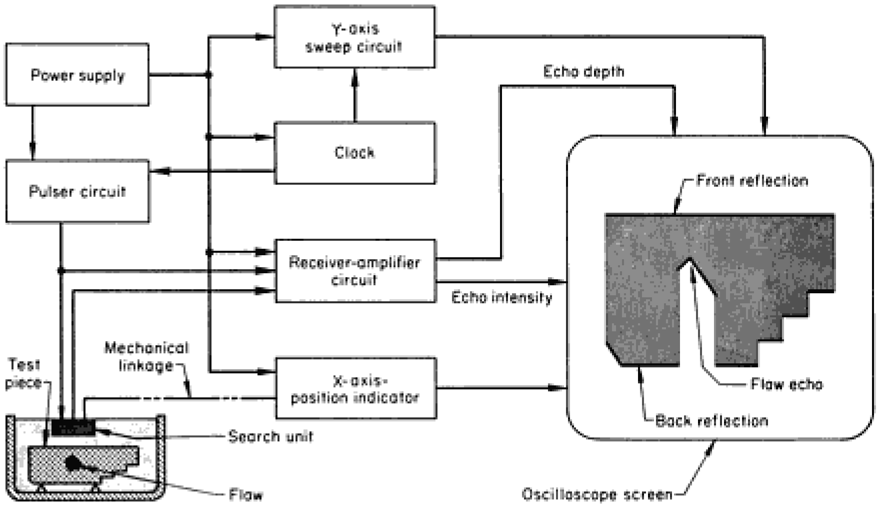


Fig. 5 Typical B-scan setup, including video-mode display, for a basic pulse-echo, ultrasonic-inspection system

The oscilloscope screen in Fig. 5 illustrates the type of video-mode display that is generated by B-scan equipment. The internal flaw in the test piece shown at left in Fig. 5 is shown only as a profile view of its top reflecting surface. Portions of the test piece that are behind this large reflecting surface are in shadow.

C-scan display records echoes from internal portions of test pieces as a function of the position of each reflecting interface within an area. Flaws are shown on a readout, superimposed on a plan view of the test piece, and both flaw size (flaw area) and position within the plan view are recorded. Flaw depth typically is not recorded, although it can be measured semiquantitatively by restricting the range of depths within the test piece that is covered in a given scan.

In a basic C-scan system, shown schematically in Fig. 6, the the search unit is moved over the surface of the test piece in a search pattern. The search pattern can take many forms, such as a series of closely spaced parallel lines, a fine zigzag pattern, and a spiral pattern (polar scan). Mechanical linkage connects the search unit to *x*-axis and *y*-axis position indicators, which in turn, feed position data to the *x-y* plotter or facsimile device. Echo-recording systems vary; some produce a shaded-line scan with echo amplitude recorded as a variation in line shading, while others indicate flaws by an absence of shading, so each flaw appears as a blank space on the display (see Fig. 6).

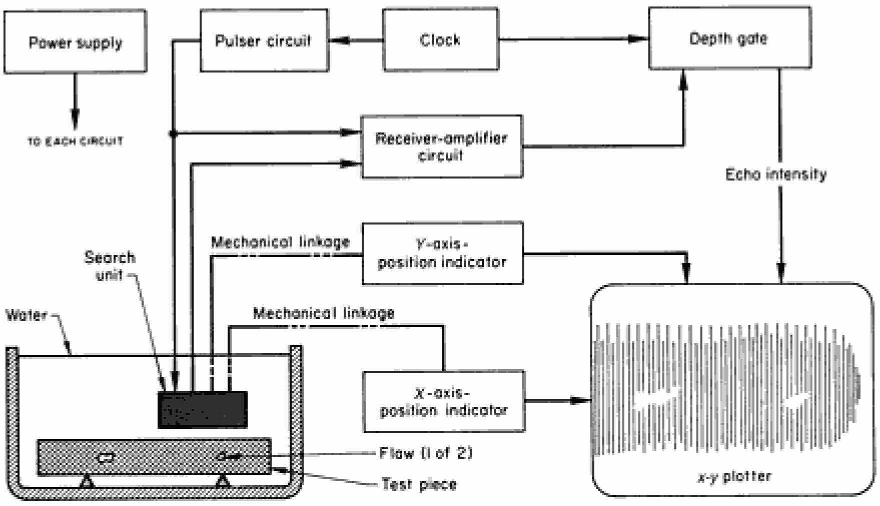

Power supply
TO EACH CIRCUIT
Pulser circuit
Clock
Depth gate
Receiver-amplifier circuit
Echo intensity
Mechanical linkage
Y-axis-position indicator
Search unit
Water
Mechanical linkage
X-axis-position indicator
Flaw (1 of 2)
Test piece
x-y plotter

Fig. 6 Typical C-scan setup, including display, for a basic pulse-echo, ultrasonic-inspection system

Interpretation of Pulse-Echo Data

Interpretation of pulse-echo data is relatively straightforward for B-scan and C-scan presentations. The B-scan always records the front reflection, while internal echoes and/or loss of back reflection are interpreted as flaw indications. Flaw depth is measured as the distance from the front reflection to a flaw echo, the latter representing the front surface of the flaw.

In contrast to normal B-scan and C-scan displays, A-scan displays can be complex. It is necessary to disregard electronic noise, spurious echoes, and extra echoes resulting from mode conversion of the initial pulse to focus attention on any flaw echoes that might be present.

Basic A-scan displays are of the type shown in Fig. 7 for immersion inspection of a plate containing a flaw. The test material is 25 mm (1 in.) thick aluminum alloy 1100 plate containing a purely reflecting planar flaw 11.25 mm (0.44 in.) deep. The flaw is 45% of plate thickness, exactly parallel to the plate surfaces, and has an area equal to one-third the cross section of the ultrasonic beam. Testing is by straight-beam immersion in a water-filled tank. There are no attenuation losses within the test plate, only transmission losses across front and back surfaces.

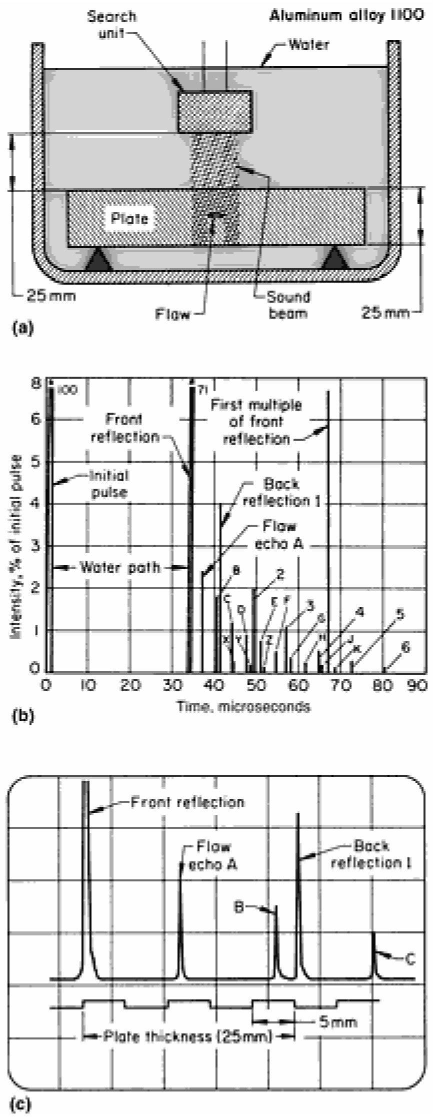

Search unit
Aluminum alloy 1100
Water
Plate
25 mm
Flaw
Sound beam
25 mm
(a)
Intensity, % of initial pulse
100
71
Front reflection
First multiple of front reflection
Initial pulse
Back reflection 1
Flaw echo A
Water path
B
2
C
D
E
F
3
G
X
Y
Z
H
4
J
K
5
6
0 10 20 30 40 50 60 70 80 90
Time, microseconds
(b)
Front reflection
Flaw echo A
Back reflection 1
B
C
5mm
Plate thickness (25mm)
(c)

Fig. 7 Schematic representation of straight-beam immersion inspection of a 25 mm thick aluminum alloy 1100 plate containing a planar discontinuity, showing (a) inspection setup, (b) complete video-mode A-scan display, and (c) normal oscilloscope display

The normal display (Fig. 7c) represents only a portion of the complete video-mode A-scan display (Fig. 7b). The normal display is obtained by adjusting horizontal-position and horizontal-sweep controls to display only the portion of the trace corresponding to the transit time (time of flight) required for a single pulse of ultrasound to traverse the test piece from front surface to back surface and return. Also, receiver-amplifier gain is adjusted until the height of the first back reflection equals some arbitrary distance on the screen, usually a convenient number of grid lines.

Most flaws are not exactly parallel to the surface of the testpiece, not truly planar (they have rough, curved interfaces), not ideal reflectors, and are of unknown size. These factors together with bulk material sound-attenuating characteristics affect echo signal size and shape.

Angle-Beam Technique. Most angle-beam testing is accomplished using shear waves, although refracted longitudinal waves and surface waves can be used in some applications. In contrast to straight-beam testing, only flaw indications appear on the display in an angle-beam test. Only rarely will a back surface be oriented properly to give a back-reflection indication. In most instances, ultrasonic beams are reflected from the back surface at an angle away from the search unit. The reflected pulses are capable of detecting discontinuities and are used extensively in angle-beam testing of welds, pipe and tubing, and sheet and plate.

The time base (horizontal sweep) on the oscilloscope must be carefully calibrated, because in angle-beam testing there is no back-reflection echo to provide a reference to estimate flaw depth. Usually, an extended time base is used so flaws are located with one or two skip distances from the search unit (see Fig. 8 for the definition of skip distance).

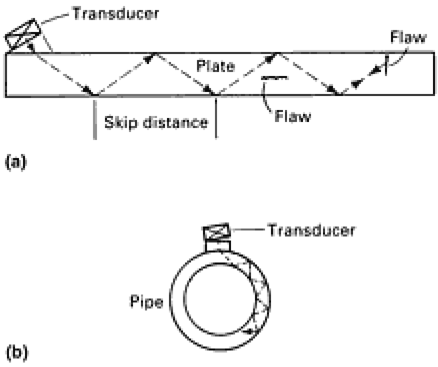

Transducer
Flaw
Plate
Skip distance
Flaw
(a)
Transducer
Pipe
(b)

Fig. 8 Angle-beam testing using a contact transducer on a (a) plate and (b) pipe

Figure 8(a) shows how a shear wave from an angle-beam transducer progresses through a flat testpiece--by reflecting from the surfaces at points called "nodes." The linear distance between two successive nodes on the same surface is called the "skip distance," and is important in defining the path over which the transducer should be moved for reliable and efficient scanning. The skip distance can easily be measured by using a separate receiving transducer to detect the nodes or by using an angle-beam test block, or it can be calculated. The region over which the transducer should be moved to scan the test piece can be determined once the skip distance is known.

Moving the search unit back and forth between one-half skip distance and one skip distance from an area of interest can be used not only to define the location, depth, and size of a flaw, but also to initially detect flaws. Figure 9 illustrates this back-and-forth movement as a way of scanning a weld for flaws.

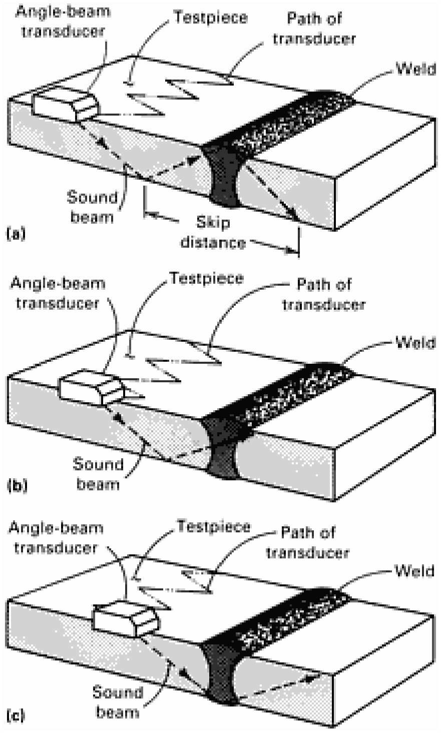

Angle-beam transducer
Testpiece
Path of transducer
Weld
Sound beam
(a)
Skip distance
Angle-beam transducer
Testpiece
Path of transducer
Weld
Sound beam
(b)
Angle-beam transducer
Testpiece
Path of transducer
Weld
Sound beam
(c)

Fig. 9 Three positions of a contact type of transducer along the zigzag scanning path used during manual angle-beam ultrasonic inspection of welded joints. The movement of the sound beam path across the weld is

shown on a section taken along the centerline of the transducer as it is moved from the far left position in the (a) scanning path, (b) through an intermediate position, (c) to the far right position.

Sometimes, moving the search unit in an arc about the position of a suspected flaw or swiveling the search unit about a fixed position can be equally useful (Fig. 10a). As shown in Fig. 10(b), traversing the search unit in an arc about the location of a gas hole produces little or no change in the echo. The indication on the oscilloscope screen remains constant in both amplitude and position on the trace as the search unit is moved. Conversely, if the search unit was swiveled on the same spot, the indication would abruptly disappear after the search unit was swiveled only a few degrees.

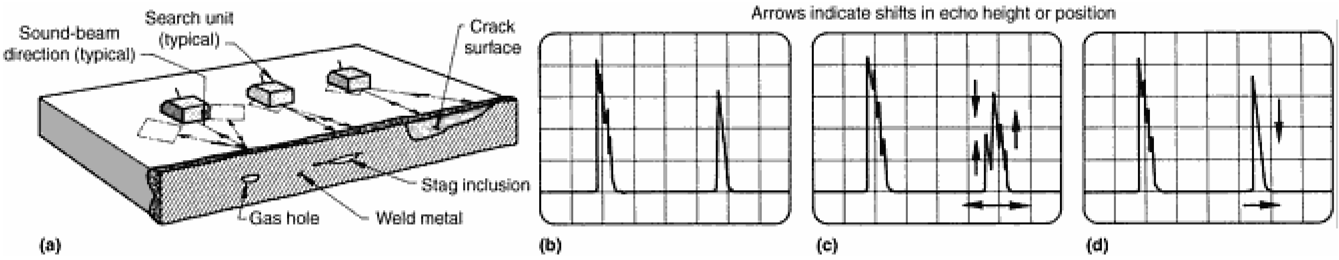

Sound-beam direction (typical)
Search unit (typical)
Crack surface
Slag inclusion
Gas hole
Weld metal
Arrows indicate shifts in echo height or position
(a)
(b)
(c)
(d)

Fig. 10 Angle-beam inspection of a weldment, showing effect of search-unit movements on oscilloscope-screen display patterns from three different types of flaws in welds. (a) Positions of search units on the test piece. (b) Display pattern obtained from a gas hole as the result of traversing the search unit in an arc about the location of the flaw. (c) Display pattern obtained from a slag inclusion as the result of swiveling the search unit on a fixed point. (d) Display pattern obtained from a crack, using the same swiveling search-unit movement as in (c)

Transmission Methods

Regardless of whether transmission ultrasonic testing is done using direct beams or reflected beams, flaws are detected by comparing the amount of ultrasound transmitted through the test piece with the amount transmitted through a reference standard made of the same material. Transmission testing requires two search units, one to transmit the ultrasonic waves and one to receive them.

The main application of transmission methods is the inspection of plate for cracks or laminations that have relatively large dimensions compared with the size of the search units. Immersion techniques and water-column (bubbler or squirter) techniques are most effective because they provide efficient and relatively uniform coupling between the search units and the test piece.

Display of transmission-test data can be oscilloscope traces, strip-chart recordings, and meter readings. Oscilloscopes are used to record data mainly when using pulsed sound beams; strip charts and meters are more appropriate for continuous beams. With all three types of display, alarms or automatic sorting devices can be used to give audible warning or to shunt defective workpieces out of the normal flow of production.

Pitch-catch testing can be done with either direct beams (through-transmission testing) or reflected beams. In both instances, pulses of ultrasonic energy pass through the material, and pulse intensities are measured at the point of emergence. An oscilloscope display is triggered simultaneously with the initial pulse, and the transmitted-pulse indication appears on the screen to the right of the initial-pulse indication in a manner similar to the back-reflection indication in pulse-echo testing. A major advantage of pitch-catch testing is that disturbances and spurious indications can be separated from the transmitted pulse by their corresponding transit times. Only the amplitude of the transmitted pulse is monitored; all other sound waves reaching the receiver are ignored. An electronic gate can be set to operate an alarm or a sorting device when the monitored amplitude of the ultrasonic wave drops below a preset value.

When reflected pulses are used, the technique is almost identical to the loss-of-back-reflection technique, which often is used in ordinary pulse-echo testing.

General Characteristics of Ultrasonic Waves

In contrast to electromagnetic waves, such as light and x-rays, ultrasonic waves are mechanical waves consisting of oscillations, or vibrations, of the atomic or molecular particles of a substance about the equilibrium position of those particles. Ultrasonic waves can propagate in elastic media, which can be solid or liquid. Ultrasonic waves in the megahertz region are severely attenuated in air and cannot propagate in a vacuum. An ultrasonic beam is similar to a light beam. Both obey general wave equations and each travels at a characteristic velocity that depends on the properties of that medium. Ultrasonic beams, like light beams, are reflected from surfaces and are refracted when they cross boundaries between two media that have different acoustic velocities. Depending on the mode of particle motion, ultrasonic waves are classified as longitudinal waves, vertically and horizontally polarized shear and transverse waves, surface waves, Lamb waves, etc. Four wave modes are described in the following paragraphs.

Longitudinal waves, sometimes called compression waves, are most widely used in the inspection of metals. They travel through metal as a series of alternate compressions and rarefactions, in which the particles transmitting the wave vibrate back and forth in the direction of travel of the waves.

Longitudinal ultrasonic waves and the corresponding particle oscillation and resultant rare-faction and compression are represented schematically in Fig. 11(a). A plot of amplitude of particle displacement versus distance of wave travel, together with the resultant rarefaction trough and compression crest, is shown in Fig. 11(b). The distance from one crest to the next (which equals the distance for one complete cycle of rarefaction and compression) is the wavelength (λ). The vertical axis in Fig. 11(b) could represent pressure instead of particle displacement. The horizontal axis could represent time instead of travel distance because the speed of sound is constant in a given material, and this relation is used in the measurements made in ultrasonic inspection.

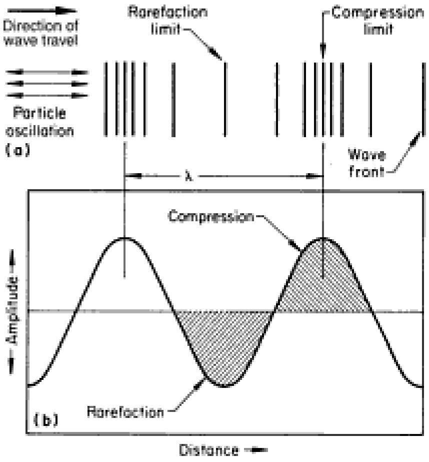


Fig. 11 Schematic representation of longitudinal ultrasonic waves. (a) Particle oscillation and resultant rarefaction and compression. (b) Amplitude of particle displacement versus distance of wave travel. The wavelength (λ) is the distance corresponding to one complete cycle.

Longitudinal ultrasonic waves are readily propagated in liquids and elastic solids. The mean free paths of the molecules of liquids are so short that longitudinal waves can be propagated simply by the elastic collision of one molecule with the next. The velocity of longitudinal ultrasonic waves is about 6000 m/s (19,700 ft/s) in steel and about 1500 m/s (4900 ft/s) in water.

Transverse waves (shear waves) also are used extensively in ultrasonic inspection of metals. Transverse waves are visualized readily in terms of vibrations of a rope that is shaken rhythmically, in which each particle vibrates up and down in a plane perpendicular to the direction of propagation. A transverse wave is represented schematically in Fig. 12, which shows particle oscillation, wave front, direction of wave travel, and the wavelength (λ) corresponding to one cycle.

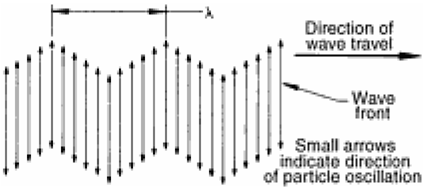


Fig. 12 Schematic representation of transverse (shear) waves. The wavelength (λ) is the distance corresponding to one complete cycle.

Air and water do not support transverse waves. In gases, the forces of attraction between molecules are so small that shear waves cannot be transmitted. The same is true of a liquid, unless it is particularly viscous or is present as a very thin layer.

Surface waves (Rayleigh waves) are another type of ultrasonic waves used in the inspection of metals. These waves travel along the flat and curved surfaces of relatively thick solid parts. For propagation of waves of this type, the waves must be traveling along an interface bounded on one side by the strong elastic forces of a solid and on the other side by the practically negligible elastic forces between gas molecules. Surface waves, therefore, are essentially nonexistent in a solid immersed in a liquid, unless the liquid covers the solid surface only as a very thin film.

Surface waves are subject to less attenuation in a given material than are longitudinal and transverse waves. They have a velocity approximately 90% of the transverse-wave velocity in the same material. The region within which these waves propagate with effective energy is not much thicker than about one wavelength beneath the surface of the metal. At this depth, wave energy is about 4% of the wave energy at the surface, and the amplitude of oscillation decreases sharply to a negligible value at greater depths.

In Rayleigh waves, particle oscillation generally follows an elliptical orbit, as shown schematically in Fig. 13. The major axis of the ellipse is perpendicular to the surface along which the waves are traveling. The minor axis is parallel to the direction of propagation. Rayleigh waves can exist in complex forms, which are variations of the simplified wave form illustrated in Fig. 13.

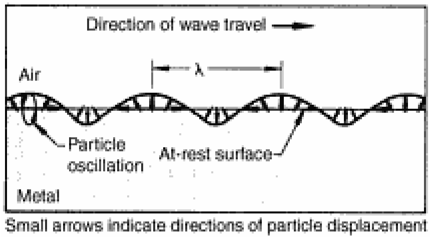


Fig. 13 Diagram of surface (Rayleigh) waves propagating at the surface of a metal along a metal-air interface. The wavelength (λ) is the distance corresponding to one complete cycle.

Lamb waves, also known as plate waves, are propagated in a mode in which the ultrasonic beam is contained within two parallel boundary surfaces (such as a plate or the wall of a tube). A Lamb wave consists of a complex vibration that occurs throughout the thickness of the material. The propagation characteristics of Lamb waves depend on the density, elastic properties, and structure of the metal, and are influenced by material thickness.

Two basic forms of Lamb waves are (a) symmetrical, or dilatational and (b) asymmetrical, or bending. The form is determined by whether the particle motion is symmetrical or asymmetrical with respect to the neutral axis of the test piece. Each form is further subdivided into several modes having different velocities, which can be controlled by the angle at which the waves enter the test piece. Theoretically, there are an infinite number of specific velocities at which Lamb waves can travel in a given material. Within a given plate, the specific velocities of Lamb waves are complex functions of plate thickness and cyclic frequency.

In symmetrical Lamb waves, there is a compressional (longitudinal) particle displacement along the neutral axis of the plate and an elliptical particle displacement on each surface (see Fig. 14a). In asymmetrical Lamb waves, there is a shear (transverse) particle displacement along the neutral axis of the plate and an elliptical particle displacement on each surface (see Fig. 14b). The ratio of the major to minor axes of the ellipse is a function of the material in which the wave is being propagated.

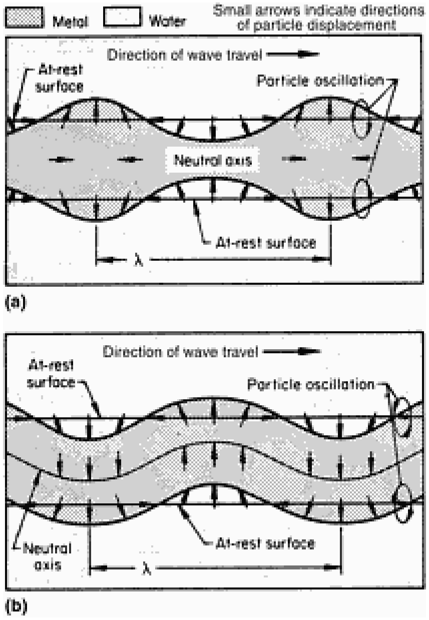

Metal
Water
Small arrows indicate directions of particle displacement
Direction of wave travel
At-rest surface
Particle oscillation
Neutral axis
At-rest surface
λ
(a)
Direction of wave travel
At-rest surface
Particle oscillation
Neutral axis
At-rest surface
λ
(b)

Fig. 14 Diagram of the basic patterns of (a) symmetrical (dilatational) and (b) asymmetrical (bending) Lamb waves. The wavelength (λ) is the distance corresponding to one complete cycle.

Factors Influencing Ultrasonic Inspection

Both the characteristics of ultrasonic waves used and the part being inspected must be considered in ultrasonic inspection. Equipment type and capability are influenced by these variables; often, different types of equipment must be selected to accomplish different inspection objectives.

Selection of inspection frequency is a compromise between the ability of the ultrasonic beam to penetrate the material and the time or depth resolution desired. A high frequency generally provides high resolution and high definition, while a lower frequency might be required to achieve the desired penetration.

Sensitivity, or the ability of an ultrasonic-inspection system to detect a very small discontinuity, generally is increased by using relatively high frequencies (short wavelengths). Frequency ranges commonly used in nondestructive testing (NDT) are listed in Table 3.

Table 3 Common ultrasonic testing frequency ranges and applications

Frequency range	Applications
200 kHz-1 MHz	Coarse-grain castings: gray iron, nodular iron, copper, and stainless steels
400 kHz-5 MHz	Fine-grain castings: steel, aluminum, brass
200 kHz-2.25 MHz	Plastics and plastic like materials
1-5 MHz	Rolled products: metallic sheet, plate, bars, and billets
2.25-10 MHz	Drawn and extruded products: bars, tubes, and shapes
1-10 MHz	Forgings
2.25-10 MHz	Glass and ceramics
1-2.25 MHz	Welds
1-10 MHz	Fatigue cracks

Acoustic Impedance. When ultrasonic waves traveling through one medium impinge on the boundary of a second medium, a portion of the incident acoustic energy is reflected back from the boundary while the remaining energy is transmitted into the second medium. The characteristic that determines the amount of reflection is the acoustic impedance of the two materials on either side of the boundary. If the impedances of the two materials are equal, there is no reflection; if the impedances differ greatly (between a metal and air, for example), there is virtually complete reflection.

This characteristic is used in ultrasonic inspection of metals to calculate the amounts of energy reflected and transmitted at impedance discontinuities, and to aid in the selection of suitable materials for effective transfer of acoustic energy between components in ultrasonic-inspection systems.

The acoustic impedance for a longitudinal wave (Z_l), in grams per square centimeter-second, is defined as the product of material density (ρ), in grams per cubic centimeter, and longitudinal-wave velocity (V_l), in centimeters per second:

$$Z_l = \rho V_l$$

Table 4 lists acoustic properties of several metals and nonmetals. The acoustic properties of metals and alloys are influenced by variations in structure and metallurgical condition. Therefore, for a given test piece, the properties may differ somewhat from the values shown in Table 4.

Table 4 Acoustic properties of several metals and nonmetals

Material	Density (ρ), g/cm^3	Sonic velocities, 10^5 cm/s			Acoustic impedance$^{(d)}$, (Z_l) 10^6 g/cm^2 · s
		$V_l^{(a)}$	$V_t^{(b)}$	$V_s^{(c)}$	
Ferrous metals					
Carbon steel, annealed	7.85	5.94	3.24	3.0	4.66
Alloy steel					
Annealed	7.86	5.95	3.26	3.0	4.68
Hardened	7.8	5.90	3.23	. . .	4.6
Cast iron	6.95-7.35	3.5-5.6	2.2-3.2	. . .	2.5-4.0
52100 steel					
Annealed	7.83	5.99	3.27	. . .	4.69
Hardened	7.8	5.89	3.20	. . .	4.6
D6 tool steel					
Annealed	7.7	6.14	3.31	. . .	4.7
Hardened	7.7	6.01	3.22	. . .	4.6
Stainless steels					
Type 302	7.9	5.66	3.12	3.12	4.47
Type 304L	7.9	5.64	3.07	. . .	4.46
Type 347	7.91	5.74	3.10	2.8	4.54
Type 410	7.67	5.39	2.99	2.16	4.13
Type 430	7.7	6.01	3.36	. . .	4.63
Nonferrous metals					
Aluminum 1100-O	2.71	6.35	3.10	2.90	1.72
Aluminum alloy 2117-T4	2.80	6.25	3.10	2.79	1.75
Beryllium	1.85	12.80	8.71	7.87	2.37
Copper C11000	8.9	4.70	2.26	1.93	4.18
Copper alloys					
C26000 (cartridge brass, 70%)	8.53	3.83	2.05	1.86	3.27
C46400 to C46700 (naval brass)	8.41	4.43	2.12	1.95	3.73
C51000 (phosphor bronze, 5% A)	8.86	3.53	2.23	2.01	3.12
C75200 (nickel silver 65-18)	8.75	4.62	2.32	1.69	4.04
Lead					
Pure	11.34	2.16	0.70	0.64	2.45
Hard (94Pb-6Sb)	10.88	2.16	0.81	0.73	2.35
Magnesium alloy M1A	1.76	5.74	3.10	2.87	1.01
Mercury, liquid	13.55	1.45	. . .	. . .	1.95
Molybdenum	10.2	6.25	3.35	3.11	6.38
Nickel					

Pure	8.8	5.63	2.96	2.64	4.95
Inconel	8.5	5.82	3.02	2.79	4.95
Inconel X-750	8.3	5.94	3.12	. . .	4.93
Monel	8.83	5.35	2.72	2.46	4.72
Titanium, commercially pure	4.5	6.10	3.12	2.79	2.75
Tungsten	19.25	5.18	2.87	2.65	9.98
Nonmetals					
Air$^{(e)}$	0.00129	0.331	. . .	. . .	0.00004
Ethylene glycol	1.11	1.66	. . .	. . .	0.18
Glass					
Plate	2.5	5.77	3.43	3.14	1.44
Pyrex	2.23	5.57	3.44	3.13	1.24
Glycerin	1.26	1.92	. . .	. . .	0.24
Oil					
Machine (SAE 20)	0.87	1.74	. . .	. . .	0.150
Transformer	0.92	1.38	. . .	. . .	0.127
Paraffin wax	0.9	2.2	. . .	. . .	0.2
Plastics					
Methylmethacrylate (Lucite, Plexiglas)	1.18	2.67	1.12	1.13	0.32
Polyamide (nylon)	1.0-1.2	1.8-2.2	. . .	. . .	0.18-0.27
Polytetrafluoroethylene (Teflon)	2.2	1.35	. . .	. . .	0.30
Quartz, natural	2.65	5.73	. . .	. . .	1.52
Rubber, vulcanized	1.1-1.6	2.3	. . .	. . .	0.25-0.37
Tungsten carbide	10-15	6.66	3.98	. . .	6.7-9.9
Water					
Liquid$^{(f)}$	1.0	1.49	. . .	. . .	0.149
Ice$^{(g)}$	0.9	3.98	1.99	. . .	0.36

(a) Longitudinal (compression) waves.

(b) Transverse (shear) waves.

(c) Surface waves.

(d) For longitudinal waves $Z_l = \rho V_l$.

(e) At standard temperature and pressure.

(f) At 4 °C (39 °F).

(g) At 0 °C (32 °F)

Angle of Incidence. Only when an ultrasonic wave is incident at right angles on an interface between two materials (normal incidence, or angle of incidence = 0°) do transmission and reflection occur at the interface without any change in beam direction. At any other angle of incidence, the phenomena of mode conversion (a change in the nature of the wave motion) and refraction (a change in direction of wave propagation) must be considered. These phenomena can affect the entire beam or only a portion of the beam. The sum total of the changes that occur at the interface depends on the angle of incidence and the velocity of the ultrasonic waves leaving the point of impingement on the interface. All possible ultrasonic waves leaving this point are shown for an incident longitudinal ultrasonic wave in Fig. 15. Not all the waves shown in Fig. 15 will be produced in any specific instance of oblique impingement of an ultrasonic wave on an interface between two materials. The waves that propagate in a given instance depend on the angle of incidence of the initial beam, the velocities of the wave forms in both materials, and the ability of a wave form to exist in a given material.

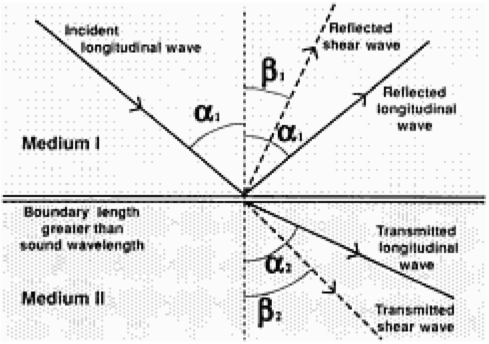

Incident longitudinal wave
Reflected shear wave
β_1
Reflected longitudinal wave
α_1
α_1
Medium I
Boundary length greater than sound wavelength
Transmitted longitudinal wave
α_2
Medium II
β_2
Transmitted shear wave

Fig. 15 Wave mode conversion at a boundary. There is an angle of incidence α_1 of the incoming longitudinal wave, such that the angle of the transmitted longitudinal wave α_2 becomes 90°. At angles of incidence greater than α_1, the longitudinal wave of velocity does not penetrate into medium II, and only the shear wave is transmitted. This is used to separate longitudinal and shear waves to have only a single wave velocity traveling in medium II.

Critical Angles. If the angle of incidence (α_1 in Fig. 15) is small, sound waves propagating in a given medium undergo mode conversion at a boundary, resulting in simultaneous propagation of longitudinal and transverse (shear) waves in a second medium. If the angle is increased, the direction of the refracted longitudinal wave will approach the plane of the boundary ($\alpha_2 \rightarrow 90°$). At some specific value of α_1, α_2 will exactly equal 90°, and the refracted longitudinal wave will disappear, leaving only a refracted (mode-converted) shear wave to propagate in the second medium. This value of α_1 is known as the "first critical angle." If α_1 is increased beyond the first critical angle, the direction of the refracted shear wave will approach the plane of the boundary ($\beta_2 \rightarrow 90°$). At a second specific value of α_1, β_2 will exactly equal 90° and the refracted transverse wave will disappear. This second value of α_1 is called the "second critical angle."

In ordinary angle-beam inspection, it usually is desirable to have only a shear wave propagating in the test material. Because longitudinal waves and shear waves propagate at different speeds, echo signals are received at different times, depending on which type of wave produces the echo. When both types are present in the test material, confusing echo patterns can be displayed on the readout device, which can lead to an erroneous interpretation. Frequently, it can be useful to produce shear waves in a material at an angle of 45° to the surface. In most materials, incident angles for mode conversion to a 45° shear wave lie between the first and second critical angles. Typical values of α_1 for all three of these (first critical angle, second critical angle, and incident angle for mode conversion to 45° shear waves) are listed in Table 5 for various metals.

Table 5 Critical angles for immersion and contact testing, and incident angle for 45° shear-wave transmission, in various metals

Metal	First critical angle, degrees[(a)], for:		Second critical angle, degrees[(a)], for:		45° shear-wave incident angle, degrees[(a)], for:	
	Immersion testing[(b)]	**Contact testing[(c)]**	**Immersion testing[(b)]**	**Contact testing[(c)]**	**Immersion testing[(b)]**	**Contact testing[(c)]**
Steel	14.5	26.5	27.5	55	19	35.5
Cast iron	15-25	28-50	. . .	. . .	. . .	. . .
Type 302 stainless steel	15	28	29	59	19.5	37
Type 410 stainless steel	11.5	21	30	63	20.5	39
Aluminum alloy 2117-T4	13.5	25	29	59.5	20	37.5
Beryllium	6.5	12	10	18	7	12.5
Copper alloy C26000 (cartridge brass, 70%)	23	44	46.5	. . .	31	67
Inconel	11	20	30	62	20.5	38.5
Magnesium alloy M1A	15	27.5	29	59.5	20	37.5
Monel	16.5	30	33	79	23	44
Titanium	14	26	29	59	20	37

(a) Measured from a direction normal to surface of test material.

(b) In water at 4 °C (39 °F).

(c) Using angle block (wedge) made of acrylic plastic.

Absorption of ultrasonic energy occurs mainly by conversion of mechanical energy into heat. Elastic motion within a substance as a sound wave propagates through it alternately heats the substance during compression and cools it during rarefaction. Because heat flows so much more slowly than an ultrasonic wave, thermal losses are incurred, which progressively reduces energy in the propagating wave. A related thermal loss occurs in polycrystalline materials: a thermoelastic loss arises from heat flow away from grains that have received more compression or expansion in the course of wave motion than did adjacent grains. For most polycrystalline materials this effect is most pronounced at the low end of the ultrasonic-frequency spectrum.

Scattering of an ultrasonic wave occurs because most materials are not truly homogeneous. Crystal discontinuities such as grain boundaries, twin boundaries, and minute nonmetallic inclusions deflect small amounts of ultrasonic energy out of the main ultrasonic beam. Also, especially in mixed microstructures and anisotropic materials, mode conversion at crystallite boundaries occurs because of slight differences in acoustic velocity and acoustic impedance across the boundaries.

Scattering is highly dependent on the relation of crystallite size (mainly grain size) to ultrasonic wavelength. When grain size is less than 0.01 times the wavelength, scatter is negligible. Scattering effects vary approximately with the third power of grain size, and when the grain size is 0.1 times the wavelength or larger, excessive scattering may make it impossible to do valid ultrasonic inspections.

Diffraction. A sound beam propagating in a homogeneous medium is coherent; that is, all particles that lie along any given plane parallel to the wave front vibrate in identical patterns. When a wave front passes the edge of a reflecting surface, the front bends around the edge in a manner similar to that in which light bends around the edge of an opaque object. When the reflector is very small compared with the sound beam, as is usual for a pore or an inclusion, wave bending (forward scattering) around the edges of the reflector produces an interference pattern in a zone immediately behind the reflector because of phase differences among different portions of the forward-scattered beam. The interference pattern consists of alternate regions of maximum and minimum intensity that correspond to regions where interfering scattered waves are in phase and out of phase, respectively.

Diffraction phenomena must be taken into account during development of ultrasonic-inspection procedures.

Near-Field and Far-Field Effects. The face of the transducer element vibrates in a complex manner, which can most easily be described as a mosaic of tiny, individual crystals, each vibrating in the same direction but slightly out of phase with its neighbors. Each element in the mosaic functions as a point (Huygens) source, and radiates a spherical wave outward from the plane of the transducer face.

Along the central axis of the composite ultrasonic beam, the series of acoustic-pressure maximums and minimums become broader and more widely spaced as the distance from the transducer face, *d*, increases. Where *d* becomes equal to *N* (length of the near field), the acoustic pressure reaches a final maximum and decreases approximately exponentially with increasing distance, as shown in Fig. 16.

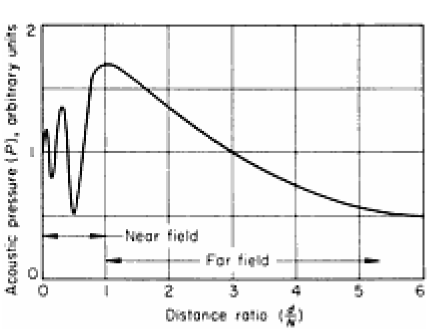


Fig. 16 Variation of acoustic pressure with distance ratio for a circular search unit. Distance ratio is distance from crystal face, *d*, divided by length of near field, *N*.

Beam Spreading. In the far field of an ultrasonic beam, the wave front expands with increasing distance from a transducer. The angle of divergence from the central axis of the beam from a circular transducer is determined from ultrasonic wavelength and transducer size.

Advantages, Disadvantages, and Applications

Advantages. The principal advantages of ultrasonic inspection compared with other methods of nondestructive inspection of metal parts are:

- Superior penetrating power, which permits detection of flaws deep in the part. Ultrasonic inspection is done routinely to depths of several feet in many types of parts and to depths of about 6 m (20 ft) in axial inspection of parts such as long steel shafts and rotor forgings.
- High sensitivity, permitting detection of extremely small flaws
- Greater accuracy than other nondestructive methods in determining the positions of internal flaws, estimating their sizes, and characterizing them in terms of nature, orientation, and shape
- Only one surface need be accessible.
- Operation is electronic, which provides almost instantaneous indications of flaws. This makes the method suitable for immediate interpretation, automation, rapid scanning, in-line production monitoring, and process control. With most systems, a permanent record of inspection results can be made.
- Volumetric scanning ability, permitting inspection of a volume of metal extending from the front surface to the back surface of a part
- Ultrasonic inspection presents no radiation hazard to operations or nearby personnel, and has no effect on equipment and materials in the vicinity
- Portability

Disadvantages of ultrasonic inspection include:

- Manual operation requires careful attention by experienced technicians.
- Technical knowledge is required to develop inspection procedures.
- Parts that are rough, irregular in shape, very small and thin, and not homogeneous are difficult to inspect.
- Discontinuities that are present in a shallow layer immediately beneath the surface might not be detectable.
- Couplants are needed to provide effective transfer of the ultrasonic beam between search units and parts being inspected.
- Reference standards are required, both to calibrate equipment and to characterize flaws.

Applications. Some of the major types of components that are ultrasonically inspected for the presence of flaws are:

- Mill components: rolls, shafts, drives, and press columns
- Power equipment: turbine forgings, generator rotors, pressure piping, weldments, pressure vessels, nuclear fuel elements, and other reactor components
- Jet-engine parts: turbine and compressor forgings, and gear blanks
- Aircraft components: forging stock, frame sections, and honeycomb sandwich assemblies
- Machinery materials: die blocks, tool steels, and drill pipe
- Railroad parts: axles, wheels, and bolted and welded rail
- Automotive parts: forgings, ductile castings, brazed and/or welded components

Ultrasonic inspection is an effective and inexpensive method for volumetric examination of structures and components of both regular and complex shapes.

Acoustic Emission Inspection

Introduction

ACOUSTIC EMISSION is defined as the high-frequency stress waves generated by the rapid release of strain energy that occurs within a material during crack growth, plastic deformation, phase transformation, etc. This energy may originate from stored elastic energy as in crack propagation, or from stored chemical-free energy as in phase transformation.

Sources of acoustic emission that generate stress waves in material include local dynamic movements such as the initiation and propagation of cracks, twinning, slip, sudden reorientation of grain boundaries, bubble formation during boiling, or martensitic phase transformations. The stresses in a metallic system may be well below the elastic design limits, and yet the region near a flaw or crack tip may undergo plastic deformation and fracture from locally high stresses, ultimately resulting in premature or catastrophic failure under service conditions.

Acoustic-emission inspection detects and analyzes minute acoustic-emission signals generated by discontinuities in materials under applied stress. Proper analysis of these signals can provide information concerning the location and structural significance of the detected discontinuities.

Another important feature of acoustic emission in general is its irreversibility. If a material is loaded to a given stress level and then unloaded, usually no emission will be observed upon immediate reloading until the previous load has been exceeded.

Types of Acoustic Emissions

Basically, there are two types of acoustic emissions: continuous and burst. The wave form of continuous-type emissions is similar to Gaussian random noise, but the amplitude varies with acoustic-emission activity. In metals and alloys, this form of emission is thought to be associated with the dislocation movements in the grains. Burst-type emissions are of short-duration pulses (ten microseconds to a few milliseconds in length) and are associated with discrete releases of strain energy. Burst-type emissions are generated by twinning, microyielding, and the development of microcracks and macrocracks. Burst-type emissions have a greater amplitude than the continuous type.

Relationship to Other Test Methods

Acoustic emission (AE) differs from most other nondestructive testing (NDT) methods in two key respects. First, the signal has its origin in the material itself, not in an external source. Second, acoustic emission detects movement, while most other methods detect existing geometrical discontinuities. Table 1 summarizes the consequences of these fundamental differences.

Table 1 Characteristics of acoustic emission inspection compared with other inspection methods

Acoustic emission	Other methods
Detects movement of defects	Detect geometric form of defects
Requires stress	Do not require stress
Each loading is unique	Inspection is directly repeatable
More material sensitive	Less material sensitive
Less geometry sensitive	More geometry sensitive
Less intrusive on plant/process	More intrusive on plant/process
Requires access only at sensors	Require access to whole area of inspection
Tests whole structure at once	Scan local regions in sequence
Main problems: noise related	Main problems: geometry related

A major benefit of AE inspection is that it allows the whole volume of the structure to be inspected nonintrusively in a single loading operation. It is not necessary to scan the structure looking for local defects; it is only necessary to connect a suitable number of fixed sensors, which are typically placed 1 to 6 m (4 to 20 ft) apart. This leads to major savings in testing large structures, for which other methods require removal of insulation, decontamination for entry to vessel interiors, or scanning of very large areas.

Typically, the global AE inspection is used to identify areas with structural problems, and other NDT methods are then used to identify more precisely the nature of the emitting defects. Depending on the case, acceptance or rejection can be based on AE inspection alone, other methods alone, or both together.

Range of Applicability

Acoustic emission is a natural phenomenon occurring in the widest range of materials, structures, and processes. The largest-scale acoustic emissions are seismic events, while the smallest-scale processes that have been observed with AE inspection are the movements of small numbers of dislocations in stressed metals. In between, there is a wide range of laboratory studies and industrial testing.

In the laboratory, AE inspection is a powerful aid to materials testing and the study of deformation and fracture. It gives an immediate indication of the response and behavior of a material under stress, intimately connected with strength, damage, and failure. Because the AE response of a material depends on its microstructure and deformation mode, materials differ widely in their AE response. Brittleness and heterogeneity are two major factors conducive to high emissivity. Ductile deformation mechanisms, such as microvoid coalescence in soft steels, are associated with low emissivity.

In production testing, AE inspection is used for checking and controlling welds, brazed joints, thermocompression bonding, and forming operations, such as shaft straightening and punch press operations. In general, AE inspection can be considered whenever the process stresses the material and produces permanent deformation.

In structural testing, AE inspection is used on pressure vessels, storage tanks, pipelines and piping, aircraft and space vehicles, electric utility plants, bridges, railroad tank cars, bucket trucks, and a range of other equipment items. Acoustic emission tests are performed on both new and in-service equipment. Typical uses include the detection of cracks, corrosion, weld defects, and material embrittlement.

Procedures for AE structural testing have been published by The American Society of Mechanical Engineers (ASME), the American Society for Testing and Materials (ASTM), and other organizations. Successful structural testing comes about when the capabilities and benefits of AE inspection are correctly identified in the context of overall inspection needs and when the correct techniques and instruments are used in developing and performing the test procedure.

Acoustic emission equipment is highly sensitive to any kind of movement in its operating frequency range (typically 20 to 1200 kHz). The equipment can detect not only crack growth and material deformation but also such processes as solidification, friction, impact, flow, and phase transformations. Therefore, AE techniques are also valuable for:

- In-process weld monitoring
- Detecting tool touch and tool wear during automatic machining
- Detecting wear and loss of lubrication in rotating equipment and tribological studies
- Detecting loose parts and loose particles
- Detecting and monitoring leaks, cavitation, and flow
- Monitoring chemical reactions, including corrosion processes, liquid-solid transformations, and phase transformations

When these same processes of impact, friction, flow, and so on, occur during a typical AE inspection for cracks or corrosion, they constitute a source of unwanted noise. Many techniques have been developed for eliminating or discriminating against these and other noise sources. Noise has always been a potential barrier to AE applicability.

Instrumentation

The key element in an AE system is a piezoelectric crystal (transducer) that converts movement into an electrical voltage. The crystal is housed in a suitable enclosure with a wear plate and a connector, as shown in Fig. 1. The sensor is excited by the stress waves impinging on its face, and it delivers an electrical signal to a nearby preamplifier and then to the main signal-processing equipment. The preamplifier can be miniaturized and housed inside the sensor enclosure, facilitating setup and reducing vulnerability to electromagnetic noise.

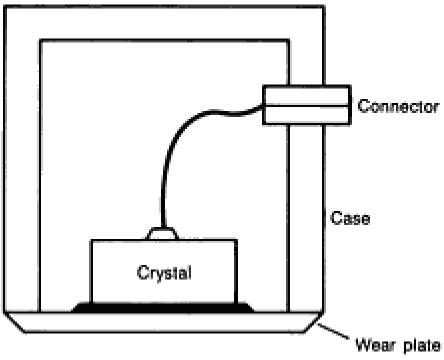


Fig. 1 Typical construction of an acoustic-emission resonant sensor

During an AE test, the sensors on the testpiece produce any number of transient signals. A signal from a single, discrete deformation event is known as a burst-type signal. This type of signal has a fast rise time and a slower decay. Burst-type signals vary widely in shape, size, and rate of occurrence, depending on the structure and the test conditions. If there is a high rate of occurrence, the individual burst-type signals combine to form a continuous emission. In some cases, AE inspection relies on the detection of continuous emission as in the case of leak testing.

The instrumentation of an AE inspection provides the necessary detection of continuous emissions or detectable burst-type emissions. Typically, AE instrumentation must fulfill several other requirements:

- The instrumentation must provide some measure of the total quantity of detected emission for correlation with time and/or load and for assessment of the condition of the testpiece.
- The system usually needs to provide some statistical information on the detected AE signals for more detailed diagnosis of source mechanisms or for assessing the significance of the detected signals.
- Many systems can locate the source of detectable burst-type emissions by comparing the arrival times of the wave at different sensors. This is an important capability of great value in testing both large and small structures.
- The systems should provide a means for discriminating between signals of interest and noise signals from background noise sources such as friction, impact, and electromagnetic interference.

Instruments vary widely in form, function, and price. Some are designed to function automatically in automated production environments. Others are designed to perform comprehensive data acquisition and extensive analysis at the hands of skilled researchers. Still others are designed for use by technicians and NDT inspectors performing routine tests defined by ASME codes or ASTM standards.

Radiography

Introduction

RADIOGRAPHY is a nondestructive-inspection method that is based on differential absorption of penetrating radiation--either electromagnetic radiation of very short wavelength or particulate radiation--by the part or test piece (object) being inspected. Because of differences in density and variations in thickness of the part, or differences in absorption characteristics caused by variations in composition, different portions of a test piece absorb different amounts of penetrating radiation. Unabsorbed radiation passing through the part can be recorded on film or photosensitive paper, viewed on a fluorescent screen, or monitored by various types of radiation detectors. The term "radiography" usually implies a radiographic process that produces a permanent image on film (conventional radiography) or paper (paper radiography or xeroradiography), although in a broad sense it refers to all forms of radiographic inspection. When inspection involves viewing of a real-time image on a fluorescent screen or image-intensifier, the radiographic process is termed "real-time inspection." When electronic, nonimaging instruments are used to measure the intensity of radiation, the process is termed "radiation gaging." Tomography, a radiation inspection method adapted from the medical computerized axial tomography CAT scanner, provides a cross-sectional view of an inspection object. All the previous terms are used mainly in connection with inspection that involves penetrating electromagnetic radiation in the form of x-rays or gamma rays. "Neutron radiography" refers to radiographic inspection using neutrons rather than electromagnetic radiation. This article discusses radiography methods using x-rays, gamma rays, and neutrons.

In conventional radiography, an object is placed in a beam of x-rays and the portion of the radiation that is not absorbed by the object impinges on a detector such as film. The unabsorbed radiation exposes the film emulsion, similar to the way that light exposes film in photography. Development of the film produces an image that is a two-dimensional "shadow picture" of the object. Variations in density, thickness, and composition of the object being inspected cause variations in the intensity of the unabsorbed radiation and appear as variations in photographic density (shades of gray) in the developed film. Evaluation of the radiograph is based on a comparison of the differences in photographic density with known characteristics of the object itself or with standards derived from radiographs of similar objects of acceptable quality.

Uses of Radiography

Radiography is used to detect features of a component or assembly that exhibit differences in thickness or physical density compared with surrounding material. Large differences are more easily detected than small ones. In general, radiography can detect only those features that have a reasonable thickness or radiation path length in a direction parallel to the radiation beam. This means that the ability of the process to detect planar discontinuities such as cracks depends on proper orientation of the test piece during inspection. Discontinuities such as voids and inclusions, which have measurable thickness in all directions, can be detected as long as they are not too small in relation to section thickness. In general, features that exhibit differences in absorption of a few percent compared with the surrounding material can be detected.

Applicability. Radiographic inspection is used extensively on castings and weldments, particularly where there is a critical need to ensure freedom from internal flaws. For instance, radiography often is specified for inspection of thick-wall castings and weldments for steam-power equipment (boiler and turbine components and assemblies) and other high-pressure systems. Radiography also can be used on forgings and mechanical assemblies. When used with mechanical assemblies, radiography provides a unique NDT capability of inspecting for condition and proper placement of components. Certain special devices are more satisfactorily inspected by radiography than by other methods. For instance, radiography is well suited to the inspection of semiconductor devices for cracks, broken wires, unsoldered connections, foreign material, and misplaced components, whereas other methods are limited in ability to inspect semiconductor devices.

Sensitivity of x-ray radiography, real-time x-ray methods, and gamma-ray radiography to various types of flaws depends on many factors, including type of material, type of flaw, and product form. (Type of material in this context is usually expressed in terms of atomic number--for instance, metals having low atomic numbers are classified as light metals and those having high atomic numbers as heavy metals.) Table 1 indicates the general degrees of suitability of the three main radiographic methods for detection of discontinuities in various product forms and applications. In some instances, radiography cannot be used even though it appears suitable from Table 1, because the part is accessible from one side only. Both sides must be accessible for radiography.

Table 1 Comparison of suitabilities of three radiographic methods for inspection of light and heavy metals

Inspection application	Suitability for light metals(a)			Suitability for heavy metals(a)		
	X-ray	**Real-time radiography(b)**	**Gamma ray**	**X-ray**	**Real-time radiography(b)**	**Gamma ray**
General						
Surface cracks(c)	F(d)	F(d)	F(d)	F(d)	F(d)	F(d)
Internal cracks	F(d)	F(d)	F(d)	F(d)	F(d)	F(d)
Voids	G	G	G	G	G	G
Thickness	F	F	F	F	F	F
Metallurgical variations	F	F	F	F	F	F
Sheet and plate						
Thickness	G(e)	G(e)	G(e)	G(e)	U	G(e)
Laminations	U	U	U	U	U	U
Voids	G	G	G	G	G	G
Bar and tube						
Seams	P	P	P	P	P	P
Pipe	G	G	G	G	F	F
Cupping	G	G	G	G	F	F
Inclusions	F	F	F	F	F	F
Castings						
Cold shuts	G	G	G	G	G	G
Surface cracks	F(d)	F(d)	F(d)	F(d)	F(d)	F(d)
Internal shrinkage	G	G	G	G	G	G
Voids, pores	G	G	G	G	G	G
Core shift	G	G	G	G	G	G
Forgings						
Laps	P(d)	P(d)	P(d)	P(d)	U	U
Inclusions	F	F	F	F	F	U
Internal bursts	G	G	G	F	F	G
Internal flakes	P(d)	P(d)	U	P(d)	P(d)	U
Cracks and tears	F(d)	F(d)	F(d)	F(d)	F(d)	F(d)
Welds						
Shrinkage cracks	G(d)	G(d)	G(d)	G(d)	G(d)	G(d)
Slag inclusions	G	G	G	G	G	G
Incomplete fusion	G	G	G	G	G	G
Pores	G	G	G	G	F	G
Incomplete penetration	G	G	G	G	G	G
Processing						
Heat treating cracks	U	F	U	P	P	U
Grinding cracks	U	F	U	U	U	U
Service						
Fatigue and heat cracks	F(d)	F(d)	P(d)	P	P	P
Stress corrosion	F	F	P	F	F	P
Blistering	P	P	P	P	P	P
Thinning	F	F	F	F	F	F
Corrosion pits	F	F	P	G	G	P

(a) G, good; F, fair; P, poor; U, unsatisfactory.

(b) Real-time radiography offers the advantage that the part can be manipulated to present the best view--for example, align a crack. Also, when microfocus, magnification methods are used, real-time radiography presents excellent resolution and contrast.

(c) Includes only visible cracks. Minute surface cracks normally are undetectable by radiographic inspection methods.

(d) Radiation beam must be parallel to the cracks, laps, or flakes.

(e) When calibrated using special thickness gages

Radiography can be used to inspect most types of solid material, with the possible exception of assemblies containing materials of very high or very low density. (Neutron radiography, however, often can be used in such instances, as discussed in the article "Thermal Inspection.") Both ferrous and nonferrous alloys can be radiographed, as can nonmetallic materials and composites.

Limitations. Compared with other nondestructive methods of inspection, radiography is expensive. Relatively large capital costs and space allocations are required for a radiographic laboratory or a real-time inspection station. Conversely, when portable x-ray or gamma-ray sources are used, capital costs can be relatively low. Operating costs can be high; large percentages of the total inspection time is spent in setting up for radiography. With real-time radiography, operating costs usually are much lower, because setup times are shorter and there are no extra costs for x-ray film and processing.

Field inspection of thick sections is a time-consuming process. Portable x-ray sources generally emit relatively low-energy radiation, up to approximately 400 keV, and also are limited as to the intensity of radiation output. These characteristics of portable sources combine to limit x-radiography in the field to sections having absorption equivalent to that of approximately 75 mm (3 in.) of steel. Radioactive sources also are limited in the thickness that can be inspected, primarily because high-activity sources require heavy shielding for protection of personnel. This limits field usage to sources of lower activity that can be transported in relatively lightweight containers. Because portable x-ray and gamma-ray sources are limited in effective radiation output, exposure times usually are long for thick sections. Recent developments, such as a portable linear accelerator, can speed up and increase the penetrating power of field radiographic methods.

Certain types of flaws are difficult to detect by radiography. Laminar defects such as cracks present problems unless they are essentially parallel to the radiation beam. Tight, meandering cracks in thick sections usually cannot be detected even when properly oriented. Minute discontinuities such as inclusions in wrought material, flakes, microporosity, and microfissures cannot be detected unless they are sufficiently segregated to yield a detectable gross effect. Laminations normally are not detectable by radiography because of their unfavorable orientation--usually parallel to the surface. Laminations seldom yield differences in absorption that enable laminated areas to be distinguished from lamination-free areas.

Principles of Radiography

Three basic elements--a radiation source or probing medium, the test piece or object being evaluated, and a recording medium (usually film)--combine to produce a radiograph. These elements are shown schematically in Fig. 1. The test piece in Fig. 1 is a plate of uniform thickness containing an internal flaw that has absorption characteristics different from those of the surrounding material. Radiation from the source is absorbed by the test piece as the radiation passes through it; the flaw and surrounding material absorb different amounts of radiation. Thus, the amount of radiation that reaches the film in the area beneath the flaw is different from the amount that impinges on adjacent areas. This produces on the film a latent image of the flaw that, when the film is developed, can be seen as a "shadow" of different photographic density from that of the image of the surrounding material.

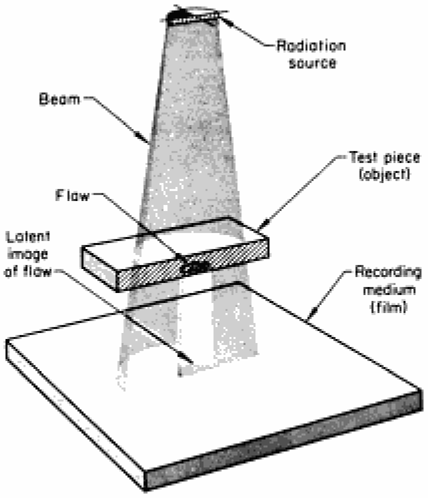


Fig. 1 Diagram of the basic elements of a radiographic system, showing method of detecting and recording an internal flaw in a plate of uniform thickness

Geometric Factors In Radiography. Because a radiograph is a two-dimensional representation of a three-dimensional object, the radiographic images of most test pieces are somewhat distorted in size and shape.

In conventional radiography, the position of a flaw within the volume of a test piece cannot be determined exactly with a single radiograph; depth in the direction of the radiation beam cannot be determined exactly. Conclusions regarding depth sometimes can be drawn from the sharpness of the flaw image. Images of flaws close to the detector tend to appear sharper than images of flaws near the source side of the object. However, techniques such as stereoradiography, tomography, triangulation, or simply making two or more exposures (with the radiation beam being directed at the test piece from a different angle for each exposure) can be used to locate flaws more exactly within the test-piece volume.

Sources of Radiation

Two types of electromagnetic radiation are used in radiographic inspection: x-rays and γ-rays. X-rays and γ-rays differ from other types of electromagnetic radiation (such as visible light, microwaves, and radio waves) only in their wavelengths, although there is not always a distinct transition from one type of electromagnetic radiation to another (Fig. 2). Only x-rays and γ-rays, because of their relatively short wavelengths (high energies), have the capability of penetrating opaque materials to reveal internal flaws.

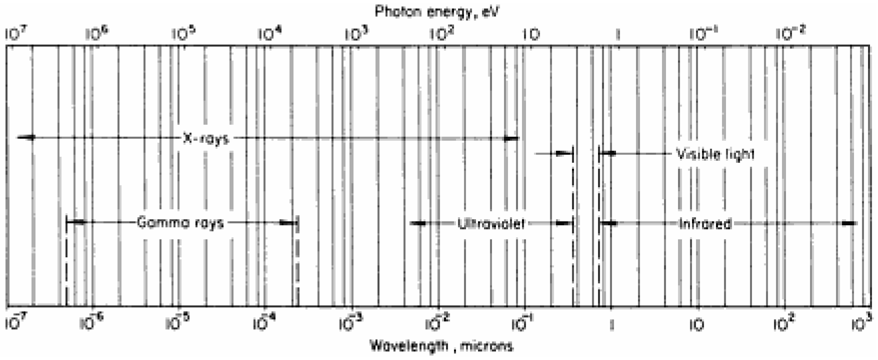


Fig. 2 Schematic representation of the portion of the electromagnetic spectrum that includes x-rays, gamma rays, ultraviolet and visible light, and infrared radiation, showing their relationship with wave length and photon energy

X-rays and γ-rays are physically indistinguishable; they differ only in the manner in which they are produced. X-rays result from the interaction between a rapidly moving stream of electrons and atoms in a solid target material, while γ-rays are emitted during the radioactive decay of unstable atomic nuclei.

The amount of exposure from x-rays or γ-rays is measured in roentgens (R), where 1 R is the amount of radiation exposure that produces one electrostatic unit (3.33564×10^{-10} C) of charge from 1.293 mg (45.61×10^{-6} oz) of air. The intensity of an x-ray or γ-ray radiation is measured in roentgens per unit time.

Although the intensity of x-ray or γ-ray radiation is measured in the same units, the strengths of x-ray and γ-ray sources are usually given in different units. The strength of an x-ray source is typically given in roentgens per minute at one meter (RMM) from the source or in some other suitable combination of time or distance units (such as roentgens per hour at one meter, or RHM). The strength of a γ-ray source is usually given in terms of the radioactive decay rate, which has the traditional unit of a Curie (1 Ci = 37×10^9 disintegrations per second). The corresponding unit in the Système International d'Unités (SI) system is a gigabecquerel (1 GBq = 1×10^9 disintegrations per second).

The spectrum of radiation is often expressed in terms of photon energy rather than as a wavelength. Photon energy is measured in electron volts, with 1 eV being the energy imparted to an electron by an accelerating potential of 1 V. Figure 2 shows the radiation spectrum in terms of both wavelength and photon energy.

Production of X-Rays. When x-rays are produced from the collision of fast-moving electrons with a target material, two types of x-rays are generated. The first type of x-ray is generated when the electrons are rapidly decelerated during collisions with atoms in the target material. These x-rays have a broad spectrum of many wavelengths (or energies) and are referred to as continuous x-rays or by the German word bremsstrahlung, which means braking radiation. The second type of x-ray occurs when the collision of an electron with an atom of the target material causes a transition of an orbital electron in the atom, thus leaving the atom in an excited state. When the orbital electrons in the excited atom rearrange themselves, x-rays are emitted that have specific wavelengths (or energies) characteristic of the particular electron rearrangements taking place. These characteristic x-rays usually have much higher intensities than the background of bremsstrahlung having the same wavelengths.

Production of γ-Rays. Gamma rays are generated during the radioactive decay of both naturally occurring and artificially produced unstable isotopes. In all respects other than their origin, γ-rays and x-rays are identical. Unlike the broad-spectrum radiation produced by x-ray sources, γ-ray sources emit one or more discrete wavelengths of radiation, each having its own characteristic photon energy (or wavelength).

Many of the elements in the periodic table have either naturally occurring radioactive isotopes or isotopes that can be made radioactive by irradiation with a stream of neutrons in the core of the nuclear reactor. However, only certain isotopes are extensively used for radiography (Table 2).

Table 2 Characteristics of γ-ray sources used in industrial radiography

γ-ray source	Half-life	Photon energy, MeV	Radiation output[(a)], RHM/Ci	Penetrating power, mm (in.) of steel
Thulium-170	128 d	0.054 and 0.084[(b)]	0.003	13 ($\frac{1}{2}$)
Iridium-192	74 d	12 rays from 0.21-0.61	0.48	75 (3)
Cesium-137	33 yr	0.66	0.32	75 (3)
Cobalt-60	5.3 yr	1.17 and 1.33	1.3	230 (9)

(a) Output for typical unshielded, encapsulated sources: RHM/Ci, roentgens per hour at 1 m per Curie.

(b) Against strong background of higher MeV radiation.

X-Ray Tubes

X-ray tubes are electronic devices that convert electrical energy into x-rays. Typically, an x-ray tube consists of a cathode structure containing a filament and an anode structure containing a target--all within an evacuated chamber or envelope (Fig. 3). A low-voltage power supply, usually controlled by a rheostat, generates the electric current that heats the filament to incandescence. This incandescence of the filament produces an electron cloud, which is directed to the anode by a focusing system and accelerated to the anode by the high voltage applied between the cathode and the anode. Depending on the size of the focal spot achieved, x-ray tubes are sometimes classified into three groups:

- Conventional x-ray tubes with focal-spot sizes between 2 by 2 mm (0.08 by 0.08 in.) and 5 by 5 mm (0.2 by 0.2 in.)
- Minifocus tubes with focal-spot sizes in the range of 0.2 mm (0.008 in.) and 0.8 mm (0.03 in.)
- Microfocus tubes with focal-spot sizes in the range of 0.005 mm (0.0002 in.) and 0.05 mm (0.002 in.)

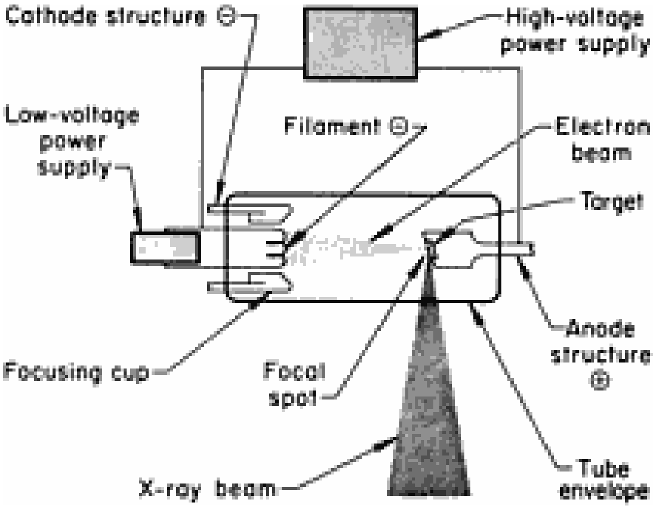


Fig. 3 **Schematic diagram of the principal components of an x-ray unit**

There are three important electrical characteristics of x-ray tubes:

- The filament current, which controls the filament temperature and in turn the quantity of electrons that are emitted
- The tube voltage, or anode-to-cathode potential, which controls the energy of impinging electrons and therefore the energy or penetrating power, of the x-ray beam
- The tube current, which is directly related to filament temperature and is usually referred to as the milliamperage of the tube

The strength, or radiation output, of the beam is approximately proportional to milliamperage, which is used as one of the variables in exposure calculations. This radiation output, or R output, is usually expressed in roentgens per minute (or hour) at 1 m.

When the accelerated electrons impinge on the target immediately beneath the focal spot, the electrons are slowed and absorbed, and both bremsstrahlung and characteristic x-rays are produced. Most of the energy in the impinging electron beam is transformed into heat, which must be dissipated. Severe restrictions are imposed on the design and selection of materials for the anode and target to ensure that structural damage from overheating does not prematurely destroy the target. Anode heating also limits the size of the focal spot. Because smaller focal spots produce sharper radiographic images, the design of the anode and target represents a compromise between maximum radiographic definition and maximum target life. In many x-ray tubes, a long, narrow, actual focal spot is projected as a roughly square effective focal spot by inclining the anode face at a small angle (usually about 20°) to the centerline of the x-ray beam, as shown in Fig. 4.

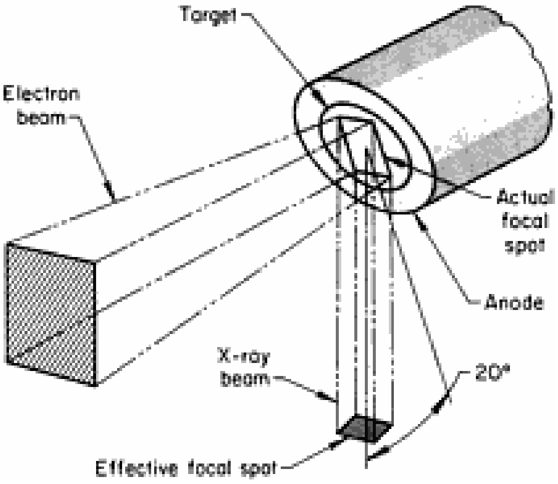


Fig. 4 Schematic diagram of the actual and effective focal spots of an anode that is inclined at 20° to the centerline of the x-ray beam

Tube Design and Materials. The cathode structure in a conventional x-ray tube incorporates a filament and a focusing cup, which surrounds the filament. The focusing cup, usually made of pure iron or pure nickel, functions as an electrostatic lens whose purpose is to direct the electron beam toward the anode. The filament, usually a coil of tungsten wire, is heated to incandescence by an electric current produced by a relatively low voltage, similar to the operation of an ordinary incandescent light bulb. At incandescence, the filament emits electrons, which are accelerated across the evacuated space between the cathode and the anode. The driving force for acceleration is a high electrical potential (voltage) between anode and cathode, which is applied during exposure.

The anode usually consists of a button of the target material embedded in a mass of copper that absorbs much of the heat generated by electron collisions with the target. Tungsten is the preferred material for traditional x-ray tubes used in radiography because its high atomic number makes it an efficient emitter of x-rays and because its high melting point enables it to withstand the high temperatures of operation. Gold and platinum are also used in x-ray tubes for radiography, but targets made of these metals must be more effectively cooled than targets made of tungsten. Other materials are used, particularly at low energies, to take advantage of their characteristic radiation. Most high-intensity x-ray tubes have forced liquid cooling to dissipate the large amounts of anode heat generated during operation.

Tube envelopes are constructed of glass, ceramic materials or metals, or combinations of these materials. X-ray tubes are inserted into metallic housings that contain an insulating medium such as transformer oil or an insulating gas. The main purpose of the insulated housing is to provide protection from high-voltage electrical shock. Housings usually contain quick disconnects for electrical cables from the high-voltage power supply or transformer. On self-contained units, most of which are portable, both the x-ray tube and the high-voltage transformer are contained in a single housing, and no high-voltage cables are used.

Microfocus X-Ray Tubes. Developments in vacuum technology and manufacturing processes have led to the design and manufacture of microfocus x-ray systems. These systems are available with voltages varying from 10 to 360 kV at beam currents from 0.01 to 2 mA. To avoid excessive pitting of the target, the beam current is varied according to the desired focal-spot size and/or kilovolt level.

Microfocus x-ray systems having focal spots that approach a point source are useful in obtaining very high resolution images. A radiographic definition of 20 line pairs per millimeter (or a spatial resolution of 0.002 in.), using real-time radiography has been achieved with microfocus x-ray sources. This high degree of radiographic definition is accomplished by image enlargement, which allows the imaging of small details.

Microfocus x-ray systems have found considerable use in the inspection of integrated circuits and other miniature electronic components. Microfocus x-ray systems with specially designed anodes as small as 13 mm (0.5 in.) in diameter and several inches long also enable an x-ray source to be placed inside otherwise inaccessible areas, such as aircraft structures and piping. The imaging medium is placed on the exterior, and this allows for the single-wall inspection of otherwise uninspectable critical components. Because of the small focal spot, the source can be close to the test area with minimal geometric unsharpness.

X-Ray Spectrum. The output of a radiographic x-ray tube is not a single-wavelength beam, but rather a spectrum of wavelengths somewhat analogous to white light. The lower limit of wavelengths, λ_{min}, in nanometers, at which there is an abrupt ending of the spectrum, is inversely proportional to tube voltage, V. This corresponds to an upper limit on photon energy, E_{max}, which is proportional to the tube voltage, V:

$$E_{max} = aV$$

where a = 1 eV/volt.

Figure 5 illustrates the effect of variations in tube voltage and tube current on photon energy and the intensity (number of photons). As shown in Fig. 5(a), increasing the tube voltage increases the intensity of radiation and adds higher-energy photons to the spectrum (crosshatched area, Fig. 5a). Conversely, as shown in Fig. 5(b), increasing the tube current increases the intensity of radiation but does not affect the energy distribution.

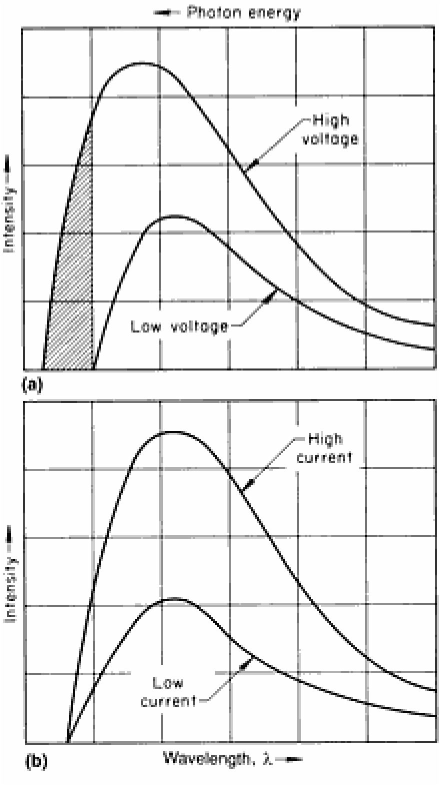


Fig. 5 Effect of (a) tube voltage and (b) tube current on the variation of intensity with wavelength for the bremsstrahlung spectrum of an x-ray tube. See text for discussion.

The energy of x-rays determines the penetration capability. Table 3 gives penetrating capabilities of x-ray beams of various energy levels expressed as the range of steel thickness that can be satisfactorily inspected. The maximum values in this table represent thicknesses of steel that can be routinely inspected using exposures of several minutes' duration and with medium-speed film. Thicker sections can be inspected for each x-ray energy value by using faster films and long exposure times, but for routine work the use of higher-energy x-rays is more practical. Sections thinner than minimum thicknesses shown in Table 3 can easily be penetrated, but radiographic contrast may not be optimum.

Table 3 Penetrating capabilities of conventional x-ray tubes and high-energy sources

Maximum accelerating potential	Penetration range for steel	
	mm	in.
X-ray tubes		
150 kV	Up to 16	Up to $\frac{5}{8}$
250 kV	Up to 38	Up to $1\frac{1}{2}$
400 kV	Up to 64	Up to $2\frac{1}{2}$
1000 kV (1 MV)	6.4 to 89	$\frac{1}{4}$ to $3\frac{1}{2}$
High-energy sources		
2.0 MeV	6.4 to 250	$\frac{1}{4}$ to 10
4.5 MeV	25 to 305	1 to 12
7.5 MeV	57 to 460	$2\frac{1}{4}$ to 18
20.0 MeV	75 to 610	3 to 24

Attenuation of Electromagnetic Radiation

X-rays and gamma rays interact with any substance, even gases such as air, as the rays pass through the substance. It is this interaction that enables parts to be inspected by differential attenuation of radiation, and that enables differences in the intensity of radiation to be detected and recorded. Both these effects are essential to the radiographic process. Attenuation characteristics of materials vary with type, intensity, and energy of the radiation, and with density and atomic structure of the material.

The attenuation of electromagnetic radiation is a complex process. The intensity of radiation varies exponentially with the thickness of homogeneous material through which it passes. This behavior is expressed as

$$I = I_0 \exp(-\mu t)$$

where I is the intensity of the emergent radiation, I_0 is the initial intensity, t is the thickness of homogeneous material, and μ is a characteristic of the material known as the linear-absorption coefficient. The coefficient μ is constant for a given situation but varies with the material and with the photon energy of the radiation. The units of μ are reciprocal length (for instance, cm^{-1}). The absorption coefficient of a material is sometimes expressed as a mass-absorption coefficient (μ/ρ), where ρ is the density of the material.

There are three primary attenuation processes: photoelectric effect, Compton scattering, and pair production.

Photoelectric effect is an interaction with orbital electrons in which a photon of electromagnetic radiation is consumed in breaking the bond between an orbital electron and its atom. Energy in excess of the bond strength imparts kinetic energy to the electron.

The photoelectric effect generally decreases with increasing photon energy (E) as $E^{-3.5}$. For elements of low atomic number, the photoelectric effect is negligible at photon energies exceeding about 100 keV. However, the photoelectric effect varies with the fourth to fifth power of atomic number; thus, for elements of high atomic number, the effect accounts for an appreciable portion of total absorption at photon energies up to about 2 MeV.

Compton scattering is a form of direct interaction between an incident photon and an orbital electron in which the electron is ejected from the atom and only a portion of the kinetic energy of the photon is consumed. The photon is scattered incoherently, emerging in a direction that is different from the direction of incident radiation and emerging with reduced energy. The relationship of the intensity of the scattered beam to the intensity of the incident beam, scattering angle, and photon energy in the incident beam is complex, yet is amenable to theoretical evaluation. Compton scattering varies directly with atomic number of the scattering element and approximately inversely with photon energy in the energy range that is of major interest.

Pair production is an absorption process that creates two 0.5 MeV photons of scattered radiation for each photon of high-energy incident radiation consumed; a small amount of scattered radiation of lower energy also accompanies pair production. Pair production is more important for heavier elements; the effect varies with atomic number, Z, approximately as $Z(Z + 1)$. The effect also varies approximately logarithmically with photon energy.

In pair production, a photon of incident electromagnetic radiation is consumed in creating an electron-positron pair that then is ejected from an atom. This effect is possible only at photon energies exceeding 1.02 MeV because, according to the theory of relativity, 0.51 MeV is consumed in the creation of the mass of each particle, electron, or positron. Any energy of the incident photon exceeding 1.02 MeV imparts kinetic energy to the pair of particles.

Radiographic Equivalence. The absorption of x-rays and gamma rays by various materials becomes less dependent on composition as radiation energy increases. For instance, at 150 kV, 25 mm (1 in.) of lead is equivalent to 350 mm (14 in.) of steel, but at 1000 kV, 25 mm of lead is equivalent to only 125 mm (5 in.) of steel. Approximate radiographic absorption equivalence factors for several metals are given in Table 4. When exposure charts are available only for certain common materials (such as steel or aluminum), exposure times for other materials can be estimated by determining the exposure time for an equal thickness of a common material from the chart, then multiplying by the radiographic equivalence factor.

Table 4 Approximate radiographic absorption equivalence for various metals

Material	X-rays, kV					X-rays, MeV			Gamma rays			
	50	**100**	**150**	**220**	**400**	**1**	**2**	**4-25**	**Ir-192**	**Cs-137**	**Co-60**	**Ra**
Magnesium	0.6	0.6	0.05	0.08	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Aluminum	1.0	1.0	0.12	0.18	. . .	. . .	. . .	. . .	0.35	0.35	0.35	0.40
Aluminum alloy 2024	2.2	1.6	0.16	0.22	. . .	. . .	. . .	. . .	0.35	0.35	0.35	. . .
Titanium	. . .	. . .	0.45	0.35	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Steel	. . .	12.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
18-8 stainless steel	. . .	12.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Copper	. . .	18.0	1.6	1.4	1.4	. . .	. . .	1.3	1.1	1.1	1.1	1.1
Zinc	. . .	. . .	1.4	1.3	1.3	. . .	. . .	1.2	1.1	1.0	1.0	1.0
Brass(a)	. . .	. . .	1.4	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.1
Inconel alloys	. . .	16.0	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Zirconium	. . .	. . .	2.3	2.0	. . .	1.0	. . .	. . .	. . .	. . .	. . .	. . .
Lead	. . .	. . .	14.0	12.0	. . .	5.0	2.5	3.0	4.0	3.2	2.3	2.0

(a) Containing no tin or lead; absorption equivalence is greater than these values when either element is present.

Principles of Shadow Formation

The image formed on a radiograph is similar to the shadow cast on a screen by an opaque object placed in a beam of light. Although radiation used in radiography penetrates an opaque object whereas light does not, the geometric laws of shadow formation are basically the same. X-rays, gamma rays, and light all travel in straight lines. Straight-line propagation is the chief characteristic of radiation that permits formation of a sharply discernible shadow. The geometric relationships of source, object, and screen to each other determine the three main characteristics of the shadow--the degrees of enlargement, distortion, and unsharpness (see Fig. 6).

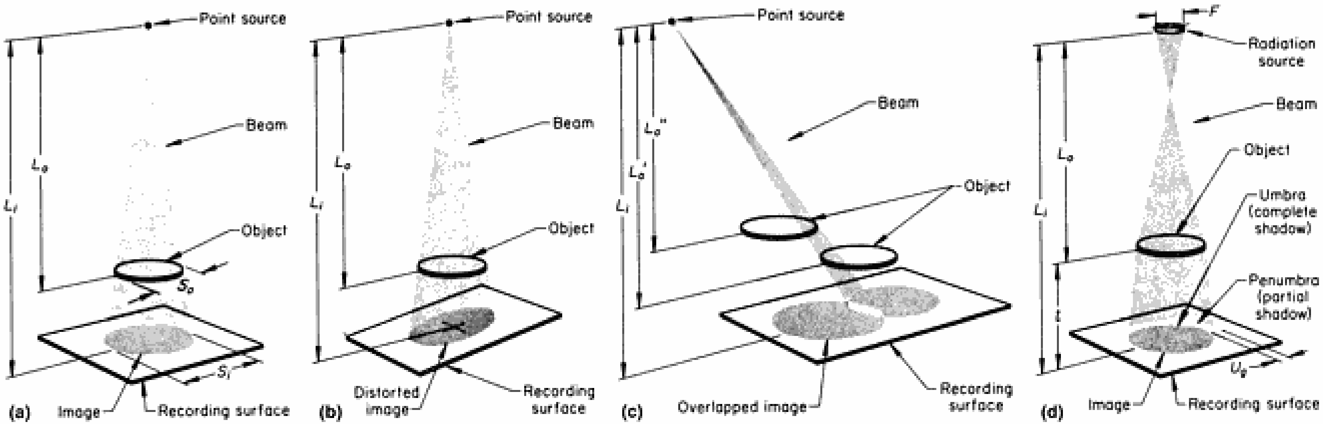


Fig. 6 Schematic representation of the effect of geometric relationships on radiographic image from point sources and actual radiation source. (a) Image size. (b) Image distortion. (c) Image overlap for point sources of radiation. (d) Degree of image unsharpness from an actual radiation source. See text for discussion. L_o = Source-to-object distance; L_i = source-to-image distance; S_o = size of object; S_i = size of image; U_g = geometric unsharpness; F = size of focal spot; t = object-to-image distance

Enlargement. The shadow of the object (test piece) is always farther from the source than the object itself. Thus, as illustrated for a point source in Fig. 6(a), dimensions of the shadow are always greater than corresponding dimensions of the object. Mathematically, the size of the image or degree of enlargement may be calculated from the relationship:

$$M = S_i/S_o = L_i/L_o$$

where M is the degree of enlargement (magnification), S_i is the size of the image, S_o is the size of the object, L_i is the source-to-image distance, and L_o is the source-to-object distance.

With very small focal spots, large values of geometric magnification can be used effectively. Values of 6 to 20 are common; magnification values as high as 100 can be used. Focal spots in microfocal x-ray equipment range from 5 to 20 μm (0.0002 to 0.0008 in.). In addition to increased image size, magnification systems also offer improved contrast because radiation scattered in the object does not reach the detector.

Distortion. As long as the plane of a two-dimensional object and the plane of the recording surface are parallel to each other, the image of that object plane will be undistorted regardless of the angle at which the beam of radiation impinges on the object. Also, the degree of enlargement for different points in a given object plane is constant because the ratio L_i/L_o is invariant. However, as shown in Fig. 6(b), if the plane of the object and the plane of the recording surface are not parallel, the image will be distorted. For objects of appreciable thickness, the magnification for different object planes will vary because L_o varies.

Geometric Unsharpness. In reality, most radiation sources are too large to be approximated by a point. Most conventional x-ray tubes have focal spots several millimeters in size. Even high-energy sources have focal spots of appreciable size, although seldom exceeding 2 mm (0.08 in.) in diameter. Gamma-ray sources vary widely in size, depending on source strength and specific activity, but seldom are less than about 2.5 mm (0.1 in.) in diameter.

Geometric unsharpness is one of several unsharpness factors, and, at low and medium x-ray energies, is usually the largest contributor to maximum unsharpness. Neglecting the distance between the actual surface of the recording medium and the adjacent (facing) surface of the test piece, which usually is quite small in relation to test-piece thickness, the geometric unsharpness can be calculated for any source size, and can be expressed as a series of straight-line plots relating geometric unsharpness, U_g, to test-piece thickness, t, for various values of source-to-object distance, L_o. A typical series is shown in Fig. 7 for a 5 mm diam (0.2 in. diam) source. It is helpful to prepare graphs like the one in Fig. 7 for each source size used.

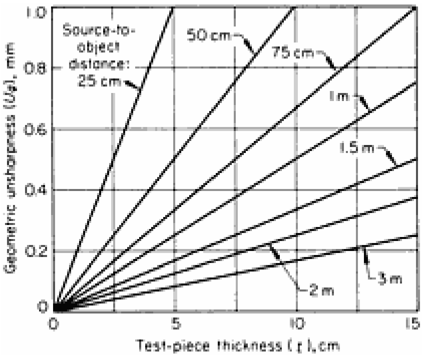


Fig. 7 Relation of geometric unsharpness to test-piece thickness for various source-to-object distances when the source is 5 mm in diameter

Image Conversion

The most important process in radiography is the conversion of radiation into a form suitable for observation or further signal processing. After penetrating the testpiece, the x-rays or γ-rays pass through a medium on the imaging surface. This medium may be a recording medium (such as film) or a medium that responds to the intensity of the radiation (such as fluorescent screen or a scintillation crystal in a discrete detector). These two types of media provide the images for subsequent observation.

Radiography can also utilize radiographic screens, which are pressed into intimate contact with the imaging medium. Radiographic screens include:

- Metallic screens placed over film, paper, or the screens used in real-time systems
- Fluorescent screens placed over film or photographic paper
- Fluorometallic screens placed over film

These screens are used to improve radiographic contrast by intensifying the conversion of radiation and by filtering the lower energy radiation produced by scattering.

Permanent images are recorded on x-ray film, radiographic paper, or electrostatically sensitive paper such as is used in the xeroradiographic process and are called radiographs. Real-time images, such as those presented on a fluorescent screen, image amplifier, or television monitor, differ in appearance from those on radiographs; records of these images may be made by photography or video recording. If the information is sensed or recorded using radiation-measuring instruments and does not appear as an image, the recording process is termed "radiation gaging." X-ray film is used more extensively than all other recording media combined.

X-ray film is constructed of a thin, transparent plastic support called a film base, which usually is coated on both sides (but occasionally on one side only) with an emulsion consisting mainly of grains of silver salts that are embedded in gelatin (see Fig. 8). These salts are very sensitive to electromagnetic radiation, especially x-rays, gamma rays, and visible light. The film base, usually tinted blue, is approximately 0.18 mm (0.007 in.) thick. An adhesive undercoat fastens the emulsion to the film base. A very thin but tough coating of gelatin called a protective overcoat covers the emulsion to protect it against minor abrasion. The total thickness of the x-ray film is approximately 0.23 mm (0.009 in.), including film base, two emulsions, two adhesive undercoats, and two protective overcoats.

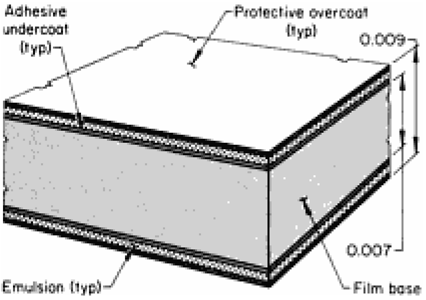


Fig. 8 Schematic cross section of a typical x-ray film

Radiographic Paper. Ordinary photographic paper can be used to record x-ray images, although its characteristics are not always satisfactory. Photographic paper has a low speed and the resulting image is low in contrast. However, photographic paper in various forms can be used effectively for some applications.

Radiographic paper can exhibit excellent sensitivity, which in many respects matches or exceeds that of fast direct-exposure x-ray films. Radiographic paper does not match the sensitivities of slow x-ray films, but because of their speed, convenience, and low cost, radiographic papers are being used both for radiography of materials that do not require critical examination and for "in-process" control.

Xeroradiography (dry radiography) is a form of imaging that uses electrostatic principles for formation of a radiographic image. In film radiography, a latent image is formed in the emulsion of a film; in xeroradiography, the latent image is formed on a plate coated with a photoconductive layer of selenium. Before use, the plate is given an even charge of static electricity over the entire surface. As soon as the plate is charged, it becomes sensitive to light as well as to x-radiation and must be protected from light by a rigid holder similar to a film cassette. In practice, the holder is used for radiography as though it contained film. X-radiation will differentially discharge the plate according to the amount of radiation received by different areas. This forms an electrostatic latent image of the test piece on the plate.

Development of the exposed plate is done by subjecting the plate, in the absence of light, to a cloud of fine powder charged opposite to the electrostatic charges remaining on the plate. The charged powder is attracted to the residual charges on the plate. The visible radiographic image can be made permanent by placing a piece of specially treated paper over the plate and transferring the powder to the paper, which then is heated to fix the powder in place.

Selenium-coated plates can be easily damaged by fingerprints, dirt, and abrasion. For this reason, automated equipment is used for charging and for development and image transfer to paper.

Flourescent screens consist of crystals that emit light in proportion to the intensity of the impinging radiation. The real-time image can then be viewed directly (with appropriate measures to protect the viewer from radiation) or can be monitored by low-level television camera tubes.

Direct viewing of flouroscopic images is known as flouroscopy. This method is the predecessor of the modern methods of real-time radiography but fluoroscopy is now largely obsolete. The main problem with fluoroscopy is the low level of light output from the fluorescent screen. This requires the suppression of background light and about 30 min for the viewer's eyes to become acclimated. Moreover, radiation safety dictates viewing through leaded glass or indirectly by mirrors. Because of these limitations, image intensities have been developed to improve safety and to amplify the images from fluorescent screens.

The modern development of low-level television camera tubes and low-noise video circuitry also allows video monitoring of the dim images on fluorescent screens. The contrast sensitivity and the spatial resolution of fluorescent-screen systems are comparable to those of image intensifiers (discussed below), but the use of fluorescent screens is limited to lower radiation energies (below about 320 keV without intensifying screens and about 1 MeV with intensifying screens). Nevertheless, fluorescent screens can provide an unlimited field of view, while image intensifiers have a field of view limited to approximately 300 mm (12 in.). The dynamic range of systems with fluorescent screens can vary from 20 to 1 for raw images to 1000 to 1 with digital processing and a large number of frames averaged.

Image-intensifier tubes are glass-enclosed vacuum devices that convert a low-intensity x-ray image or a low-brightness fluorescent-screen image into a high-brightness, visible-light image. Image intensification is achieved by a combination of electronic amplification and image minification. The image brightness at the output window of an image-intensifier tube is approximately 0.3 × 10^3 cd/m^2 (10^{-1} lambert) as compared to approximately 0.3 cd/m^2 (10^{-4} lambert) for conventional fluoroscopic screen.

The early image intensifiers were originally developed for medical purposes and were limited to applications with low-energy radiation (because of low detection efficiencies at high energies). Consequently, industrial radiography with these devices was restricted to aluminum, plastics, or thin sections of steel. By the mid-1970s, other technological developments led to further improvements such as high-energy, x-ray sensitivity for image intensifiers, improved screen materials, digital video processing for image enhancement, and high-definition imaging with microfocus x-ray generators.

The early image intensifiers were only suitable for medical applications and the inspection of light materials and thin sections of steel. The image quality was not sufficient for general use in radiography, and, image intensifiers had to be redesigned for industrial material testing. The modern image intensifier for industrial application is a very practical imaging device for radiographic inspection with radiation energies up to 10 MeV. With the image intensifier, a 2% difference in absorption can be routinely achieved in production inspection applications. The typical dynamic range of an image intensifier before image processing is about 2000 to 1.

Digital Radiography. Another method of radiographic imaging involves the formation of an image by scanning a linear array of discrete detectors along the object being irradiated. This method directly digitizes the radiometric output of the detectors and generates images in near real time. Direct digitization (as opposed to digitizing the output of a TV camera or image intensifier) enhances the signal-to-noise ratio and can result in a dynamic range up to 100,000 to 1. The large dynamic range of digital radiography allows the inspection of parts having a wide range of thicknesses and densities. Discrete detector arrangements also allow the reduction of secondary radiation from scattering by using a fan-beam detector arrangement like that of computed tomography (CT) systems. In fact, industrial CT systems are used to obtain digital radiographs. The imaging performance with detector arrays is also comparable with that of computed tomography (Table 5).

Table 5 Comparison of performance characteristics for film radiography, real-time radiography, and x-ray computed tomography

Performance characteristic	Film radiography	Real-time radiography(a)	Computed tomography or digital radiography(b)
Spatial resolution(c)	>5 line pairs/mm	~2.5 line pairs/mm	0.2-4.5 line pairs/mm
Absorption efficiencies, %			
Absorption efficiency (80 keV)	5	20	99
Absorption efficiency (420 keV)	2	8	95
Absorption efficiency (2 MeV)	0.5	2	80
Sources of noise	Scatter, poor photon statistics	Scatter, poor photon statistics	Minimal scatter
Dynamic range	200-1000	500-2000	Up to 1 × 10^6
Digital image processing	Poor, requires film scanner	Moderate to good; typically 8 bit data	Excellent; typically 16 bit data
Dimensioning capability	Moderate; affected by structure visibility and variable radiographic magnification	Moderate to poor; affected by structure visibility, resolution, variable radiographic magnification, and optical distortions	Excellent; affected by resolution, enhanced by low contrast detectability

(a) General characteristics of real-time radiography with fluorescent screen-TV camera system or an image intensifier.

(b) Digital radiographic imaging performance with discrete element detector arrays is comparable to computed tomography performance values.

(c) Can be improved with microfocus x-ray source and geometric magnification

The detectors used in digital radiography include scintillator photodetectors, phosphor photodetectors, photomultiplier tubes, and gas ionization detectors. Scintillator and phosphor photodetectors are compact and rugged, and they are used in flying-spot and fan-beam detector arrangements. Photomultiplier tubes are fragile and bulky, but do provide the capability of photon counting when signal levels are low. Gas ionization detectors have low detection efficiencies but better long-term stability than scintillator- and phosphor-photodetector arrays.

A typical phosphor-photodetector array for the radiographic inspection of welds consists of 1024 pixel elements with 25 μm (1 mil) spacing, covering 25 mm (1 in.) in length perpendicular weld seam. The linear photodiode array is covered with a fiberoptic faceplate and can be cooled in order to reduce noise. For the conversion of the x-rays to visible light, fluorescent screens are coupled to the array by means of the fiber optics. A linear collimator parallel to the array is arranged in front of the screen. The resolution perpendicular to the array is defined by the width of this slit and the speed of the manipulator. A second, single-element detector is provided to detect instabilities of the x-ray beam. Using 100 kV radiation, a spatial resolution of 0.1 mm (0.004 in.) can be achieved with a scanning speed of 1 to 10 mm/s (0.04 to 0.4 in./s).

The data from the detector system are digitized and then stored in a fast dual-ported memory. This permits quasi-simultaneous access to the data during acquisition. Before the image is stored in the frame buffer and displayed on the monitor, simple preprocessing can be done, such as intensity correction of the x-ray tube by the data of the second detector and correction of the sensitivity for different array elements. If further image processing or automatic defect evaluation is required, the system can be equipped with fast image-processing hardware. All standard devices for digital storage can be utilized.

Image Processing. Because real-time systems generally do not provide the same level of image quality and contrast as radiographic film, image processing is often used to enhance the images from image intensifiers, fluorescent screens, and detector arrays. With image processing, the video images from real-time systems can compete with the image quality of film radiography. Moreover, image processing also increases the dynamic range of real-time systems beyond that of film (which typically has a dynamic range of about 1000 to 1).

Images can be processed in two ways: as an analog video signal and as a digitized signal. An example of analog processing is to shade the image after the signal leaves the camera. Shading compensates for irregularities in brightness across the video image due to thickness or density variations in the testpiece. This increases the dynamic range (or latitude) of the system, which allows the inspection of parts having larger variations in thickness and density.

After analog image processing, the images can be digitized for further image enhancement. This digitization of the signal may involve some detector requirements. In all real-time radiological applications, the images have to be obtained at low dose rates (around 20 μR/s). In digital x-ray imaging, however, the most often used dose is around 1 mR, in order to reduce the signal fluctuations that would result from a weak x-ray flux. This means that only a short exposure time (of the order of a few milliseconds) and a frequency of several images can be used if kinetic (motion) blurring is to be avoided. The resulting requirements for the x-ray detector are therefore:

- The capability of operating properly in a pulsed mode, which calls for a fast temporal response
- An excellent linearity, to allow the use of the simplest and most efficient form of signal processing
- A wide operating dynamic range in terms of dose output (around 2000 to 1)

Once the image from the video camera has been digitized in the image processor, a variety of processing techniques can be implemented. The image-processing techniques may range from the relatively simple operation of frame integration to more complex operations such as automatic defect evaluation.

Radiation Gaging. Radiation-measuring instruments do not produce images. The output from these instruments is a meter reading or a strip chart, which records the radiation transmitted through a test piece in terms of roentgens. Many of these instruments are routinely used to check areas surrounding a radiographic-inspection site for excessive radiation.

Radiation gaging can be applied to certain automated processes, such as thickness gaging of materials or determination of liquid levels in sealed containers. In these applications, it may not be necessary to actually measure the amount of radiation passing through the material, but only to detect changes in the level of radiation--in other words, for a "go, no-go" type of inspection.

When a highly absorbing material such as thick lead or concrete must be inspected for voids and when usual radiographic techniques are impractical, radiation gaging can be used effectively. Voids can be located in these materials by noting increases in the readings of radiation-detecting instruments.

Computed Tomography. Cross-sectional images of an inspection object can be obtained by a series of radiation attenuation measurements all around the object. Typically, a fan beam of radiation about 1 or 2 mm in height is used along with a bank of detectors on the opposite side of the object. The attenuation data permit a computer reconstruction showing density differences in the cross section of the object (Fig. 9a).

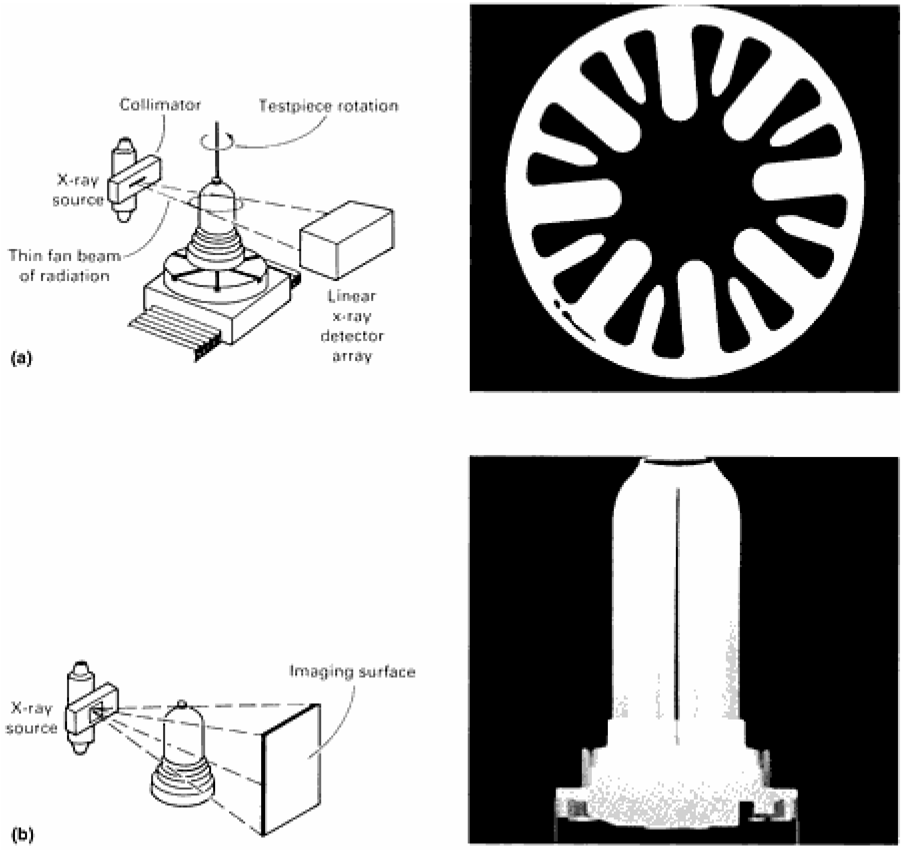


Fig. 9 Comparison of (a) computed tomography (CT) and (b) radiography. A high-quality digital radiograph (b) of a solid rocket motor igniter shows a serious flaw in a carefully oriented tangential shot. A CT image (a) at the height of the flaw shows the flaw in more detail and in a form an inexperienced viewer can readily recognize.

X-ray computed tomography has many of the same benefits and limitations as film and real-time radiography. The primary difference is the nature of the radiological image. Radiography (Fig. 9b) compresses the structural information from a three-dimensional volume into a two-dimensional image. This is useful in that it allows a relatively large volume to be interrogated and represented in a single image. This compression, however, limits the information and reduces the sensitivity to small variations. Radiographic images also can be difficult to interpret because of shadows from overlying and underlying structures superimposed on the features of interest. In contrast, the CT method provides sufficient information to localize a feature (Fig. 9a).

Some of the performance characteristics of radiography and computed tomography are compared in Table 5.

One of the limitations of CT inspection is that the CT image provides detailed information only over the limited volume of the cross-sectional slice. Full inspection of the entire volume of a component with computed tomography requires many slices, limiting the inspection throughput of the system. Therefore, CT equipment is often used in a digital radiography (DR) mode during production operations, with the CT imaging mode used for specific critical areas or to obtain more detailed information on indications found in the DR image. Digital radiography capabilities and throughput can be significant operational considerations for the overall system usage. Computed tomography systems generally provide a DR imaging mode, producing a two-dimensional radiographic image of the overall testpiece.

Characteristics of X-Ray Film

Three general characteristics of film--speed, gradient, and graininess--are primarily responsible for the performance of the film during exposure and processing and for the quality of the resulting image. Film speed, gradient, and graininess are interrelated; that is, the faster the film, the larger the graininess and the lower the gradient--and vice versa. Film speed and gradient are derived from the characteristic curve for a film emulsion, which is a plot of film density versus the exposure required for producing that density in the processed film. Graininess is an inherent property of the emulsion, but can be influenced somewhat by the conditions of exposure and development.

The selection of radiographic film for a particular application is generally a compromise between the desired quality of the radiograph and the cost of exposure time. This compromise occurs because slower films generally provide a higher film gradient and a lower level of graininess and fog.

Film Types. The classification of radiographic film is complicated, as evidenced by changes in ASTM standard practice E 94. The 1988 edition (and subsequent editions) of ASTM E 94 references an ASTM E 746, which describes a standard test method for determining the relative image-quality response of industrial radiographic film. Careful study of ASTM E 746 is required to arrive at a conclusive classification index suitable for the given radiographic film requirements of a facility.

Earlier editions (1984 and prior) of ASTM E 94 contained a table listing the characteristics of industrial films grouped into four types. Table 6 summarizes the general characteristics of these four types. This relatively simple classification method is referenced by many codes and specifications, which may state only that a type 1 or 2 film can be used for their specification requirements. However, because of this relatively arbitrary method of classification, many film manufacturers may be reluctant to assign type numbers to a given film. Moreover, the characteristics of radiographic films can vary within a type classification of Table 6 because of inherent variations among films produced by different manufacturers under different brand names and because of variations in film processing that affect both film speed and radiographic density. These variations make it essential that film processing be standardized and that characteristic curves for each brand of film be obtained from the film manufacturer for use in developing exposure charts.

Table 6 General characteristics of the four types of radiographic film specified in the earlier (1984) edition of ASTM E 94

Film type	Film characteristic		
	Speed	**Gradient**	**Graininess**
1	Low	Very high	Very fine
2	Medium	High	Fine
3	High	Medium	Coarse
4[a]	Very high[b]	Very high[b]	[c]

(a) Normally used with fluorescent screens.

(b) When used with fluorescent screens.

(c) Graininess is mainly a characteristic of the fluorescent screens.

(d) When used for direct exposure or with lead screens. These groupings are given only for qualitative comparisons. For a more detailed discussion on film classification, see the section "Film Types" in this article.

Because the variables that govern the classification of film are no longer detailed in ASTM E 94, it is largely the responsibility of the film manufacturer to determine the particular type numbers associated with his brand names. Some manufacturers indicate the type number together with the brand name on the film package. If there is doubt regarding the type number of a given brand, it is advisable to consult the manufacturer. Most manufacturers offer a brand of film characterized as very low speed, ultrahigh gradient, and extremely fine grain.

Film selection for radiography is a compromise between the economics of exposure (film speed and latitude) and the quality desired in the radiograph. In general, fine-grain, high-gradient films produce the highest-quality radiographs. However, because of the low speed typically associated with these films, high-intensity radiation or long exposure times are needed. Other factors affecting radiographic quality and film selection are the type and thickness of the testpiece and the photon energy of the incident radiation.

Although the classification of film is more complex than the types given in Table 6, a general guide is that better radiographic quality will be promoted by the lowest type number in Table 6 that economic and technical considerations will allow. In this regard, Table 7 suggests a general comparison of film characteristics for achieving a reasonable level of radiographic quality for various metals and radiation-source energies. It should be noted, however, that the film types are only a qualitative ranking of the general film characteristics given in Table 6. Many radiographic films, particularly those designed for automatic processing, cannot be adequately classified according to the system in Table 6. This compounds the problem of selecting film for a particular application.

Table 7 Guide to the selection of radiographic film for steel, aluminum, bronze, and magnesium in various thicknesses

Thickness		Type of film[(a)] for use with these x-ray tube voltages, or radioactive isotopes:										
mm	**in.**	**50-80 kV**	**80-120 kV**	**120-150 kV**	**150-250 kV**	**Ir-192**	**250-400 kV**	**1 MeV**	**Co-60**	**2 MeV**	**Ra**	**6-31 MeV**
Steel												
0-6	0-$\frac{1}{4}$	3	3	2	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6-13	$\frac{1}{4}$-$\frac{1}{2}$	4	3	2	2	. . .	1	. . .	. . .	. . .	. . .	. . .
13-25	$\frac{1}{2}$-1	. . .	4	3	2	2	2	1	. . .	1	2	. . .
25-50	1-2	. . .	. . .	. . .	3	2	2	1	2	1	2	1
50-100	2-4	. . .	. . .	. . .	4	3	4	2	2	2	3	1
100-200	4-8	. . .	. . .	. . .	. . .	. . .	4	3	3	2	3	2
>200	>8	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	3	. . .	2
Aluminum												
0-6	0-$\frac{1}{4}$	1	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6-13	$\frac{1}{4}$-$\frac{1}{2}$	2	1	1	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .
13-25	$\frac{1}{2}$-1	2	1	1	1	. . .	1	. . .	. . .	. . .	. . .	. . .
25-50	1-2	3	2	2	1	1	1	. . .	. . .	. . .	. . .	. . .
50-100	2-4	4	3	2	2	1	2	. . .	. . .	. . .	. . .	. . .
100-200	4-8	. . .	4	3	3	2	3	. . .	. . .	. . .	. . .	. . .
>200	>8	. . .	. . .	. . .	. . .	4	. . .	. . .	. . .	. . .	. . .	. . .
Bronze												
0-6	0-$\frac{1}{4}$	4	3	2	1	1	1	1	. . .	. . .	. . .	. . .
6-13	$\frac{1}{4}$-$\frac{1}{2}$	. . .	3	2	2	2	1	1	. . .	1	. . .	. . .
13-25	$\frac{1}{2}$-1	. . .	4	4	3	2	2	1	2	1	2	. . .
25-50	1-2	. . .	. . .	4	4	3	3	1	2	1	2	1
50-100	2-4	. . .	. . .	. . .	. . .	3	4	2	3	2	3	1
100-200	4-8	. . .	. . .	. . .	. . .	. . .	. . .	3	3	2	. . .	2
>200	>8	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	3	. . .	2
Magnesium												
0-6	0-$\frac{1}{4}$	1	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
6-13	$\frac{1}{4}$-$\frac{1}{2}$	1	1	1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
13-25	$\frac{1}{2}$-1	2	1	1	. . .	1	. . .	. . .	. . .	. . .	. . .	. . .
25-50	1-2	2	1	1	1	1	. . .	. . .	. . .	. . .	. . .	. . .
50-100	2-4	3	2	2	1	2	. . .	. . .	. . .	. . .	. . .	. . .
100-200	4-8	. . .	3	2	2	3	. . .	. . .	. . .	. . .	. . .	. . .
>200	>8	. . .	. . .	. . .	4	. . .	. . .	. . .	. . .	. . .	. . .	. . .

(a) These recommendations represent a usually acceptable level of radiographic quality and are based on the qualitative classification of films defined in Table 6. Optimum radiographic quality will be promoted by use of the lowest-number film type that economic and technical considerations will allow. The recommendations for type 4 film are based on the use of fluorescent screens.

Exposure Factors

Exposure is the intensity of radiation multiplied by the time during which it acts; that is, the amount of energy that reaches a particular area of the film and that is responsible for producing a particular density on the developed film. Density is the quantitative measure of blackening of a photographic emulsion. Density, measured directly with an instrument called a densitometer, is the logarithm of the ratio of the light intensity incident on the film to that transmitted by the film. Therefore, a film with a density of 1.0 will transmit only 10% of the light, a film with a density of 2.0 will transmit only $\frac{1}{100}$ of the light, and so on.

There are two kinds of density: (a) the density associated with transparent-base radiographic film, called transmission density, and (b) the density associated with opaque-base imaging material such as radiographic paper, called reflection density.

The exposure time in film radiography depends mainly on film speed, the intensity of radiation at the film surface, the characteristics of any screens used, and the desired level of photographic density. In practice, the energy of the radiation is first chosen to be sufficiently penetrating for the type of material and thickness to be inspected. The film type and the desired photographic density are then selected according requirements for contrast sensitivity (as discussed below). Once these factors are fixed, then the source strength, the source-to-film distance, and the characteristics of any screens used determine the exposure time.

With a given type of film and screen, the exposure time to produce the desired photographic density can be determined. Because intensity is inversely proportional to the square of distance from the source, the reciprocity law for equivalent exposures with an x-ray tube can be written as:

$$\frac{i_1 t_1}{L_1^2} = \frac{i_2 t_2}{L_2^2}$$

where *i* is the tube current, *t* is the exposure time, *L* is the source-to-film distance, and the subscripts refer to two different combinations that produce images with the desired photographic density. The parallel expression that applies to exposures made with a γ-ray source is:

$$\frac{a_1 t_1}{L_1^2} = \frac{a_2 t_2}{L_2^2}$$

where *a* is the source strength in gigabecquerel (Curies).

Contrast sensitivity refers to the ability of responding to and displaying small variations in subject contrast. Contrast sensitivity depends on the characteristics of the image detector and on the level of radiation being detected (or on the amount of exposure for films). The relationship between the contrast sensitivity and the level of radiation intensity (or film exposure) can be illustrated by considering two extremes. At low levels of radiation intensity, the contrast sensitivity of the detectors is reduced by a smaller signal-to-noise ratio, while at high levels, the detectors become saturated. Consequently, contrast sensitivity is a function of dynamic range (see below).

In film radiography, the contrast sensitivity is:

$$\text{Contrast sensitivity \%} = \frac{2.3\Delta D}{G_D} \times 100$$

where ΔD is the smallest change in photographic density that can be observed when the film is placed on an illuminated screen. The factor G_D is called the film gradient or film contrast. The film gradient is the inherent ability of a film to record a difference in the intensity of the transmitted radiation as a difference in photographic density. It depends on film type, development procedure, and film density. For all practical purposes, it is independent of the quality and distribution of the transmitted radiation.

Contrast sensitivity in real-time systems is determined by the number of bits (if the image is digitized) and the signal-to-noise ratio (which is affected by the intensity of the radiation and the efficiency of the detector). The best contrast sensitivity of digitized images from fluorescent screens is about 8 bits (or 256 gray levels).

Another way of specifying the contrast sensitivity of fluorescent screens is with a gamma factor, which is defined by the fractional unit change in screen brightness, $\Delta B/B$, for a given fractional change in the radiation intensity, $\Delta I/I$. Most fluorescent screens have a gamma factor of about one, which is not a limiting factor. At low levels of intensity, however, the contrast is reduced because of quantum mottle (which is a form of screen unsharpness). Unsharpness may reduce the contrast depending on flaw size (Fig. 10).

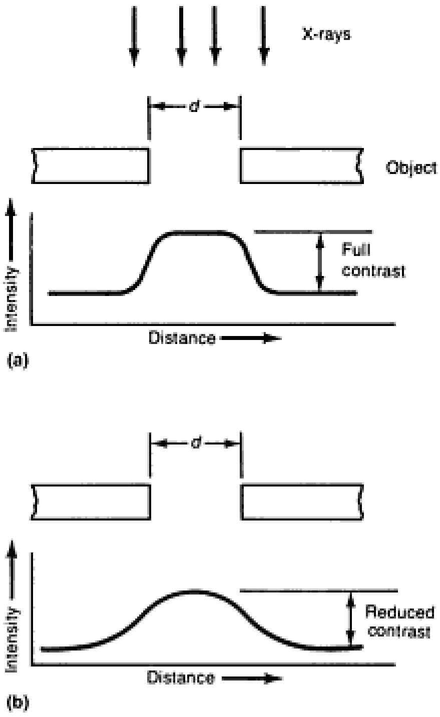


Fig. 10 Effect of geometric unsharpness on image contrast. (a) Flaw size, *d*, is larger than the unsharpness, then full contrast occurs. (b) Flaw size, *d*, is smaller than the unsharpness, then contrast is reduced.

Dynamic range, or latitude, describes the ability of the imaging system to produce a suitable signal over a range of radiation intensities. The dynamic range is given as the ratio of the largest signal that can be measured to the precision of the smallest signal that can be discriminated. A large dynamic range allows the system to maintain contrast sensitivity over a wide range of radiation intensities or testpiece thicknesses. Film radiography has a dynamic range of up to 1000 to 1, while digital radiography with discrete detectors can achieve 100,000 to 1.

The latitude, or dynamic range, of film techniques is the range of testpiece thickness that can be recorded with a single exposure. High-gradient films generally have narrow latitude, that is, only a narrow range of testpiece thickness can be imaged with optimum density for interpretation. If the testpiece is of nonuniform thickness, more than one exposure may have to be made (using different x-ray spectra or different exposure times) for complete inspection of the piece. The number of exposures, as well as the exposure times, can often be reduced by using a faster film of lower gradient but wider latitude, although there is usually an accompanying reduction in ability to image small flaws.

Exposure Charts for X-Ray Radiography. Equipment manufacturers usually publish exposure charts for each type of x-ray generator that they manufacture. These published charts, however, are only approximations; each particular unit and each installation is unique. Radiographic density is affected by such factors as radiation spectrum, film processing, setup technique, amount and type of filtration, screens, and scattered radiation.

Although published exposure charts are acceptable guides for equipment selection, more accurate charts that are prepared under normal operating conditions are recommended for each x-ray machine. A simple method for preparing accurate exposure charts is as follows:

1. Make a series of radiographs of a calibrated multiple-thickness step wedge, using several different values of exposure at each of several different tube voltage settings.
2. Process the exposed films together under conditions identical to those that will be used for routine application.
3. From the several densities corresponding to different thicknesses, determine which density (and thickness) corresponds exactly with the density desired for routine application. This step must be done with a densitometer because no other method is accurate. If the desired density does not appear on the radiograph, the thickness corresponding to the desired density can be found by interpolation.
4. Using the thickness determined in step 3 and the tube voltage (kilovoltage) and exposure (milliamp second or milliamp min) corresponding to that piece of film, plot the relation of thickness to exposure on semilogarithmic paper with exposure on the logarithmic scale.
5. Draw lines of constant tube voltage through the corresponding points on the graph.

Spectral Sensitivity. The shape of the characteristic curve of a given x-ray film is for all practical purposes unaffected by the wavelength distribution in the x-ray or gamma-ray beam used for the exposure. However, the sensitivity of the film in terms of roentgens required to produce a given density is strongly affected by radiation energy (beam spectrum of a given kilovoltage or given gamma-ray source).

Figure 11 shows the exposure required for producing a density of 1.0 on type 4 radiographic film developed in an x-ray developer (made from powder) for 5 min at 20 °C (68 °F). The exposures were made directly, without screens. The spectral-sensitivity curves for all x-ray films have approximately the same general features as the curves shown in Fig. 11.

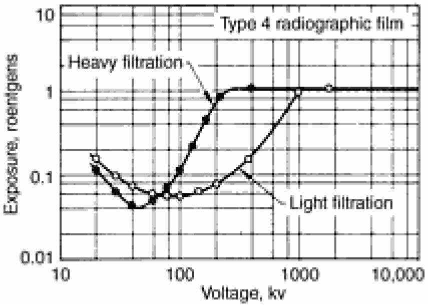


Fig. 11 Spectral-sensitivity curves for a type 4 radiographic film, showing exposure required to produce a density of 1.0

The classification of radiographic film is complicated; however, a relatively simple classification has been adopted by ASTM. According to the classification in ASTM E 94, radiographic films are grouped into four types. The general characteristics of these four types are summarized in Table 6. The relative image quality of x-ray film can also be determined in a quantitative manner using a multihole test piece as described in ASTM E 746.

Screens are often used with x-ray films during exposure. Metal screens, typically used at x-ray energies of over 150 kV, intensify the image by emission of photoelectrons and help reduce the effects of scatter by attenuating the lower-energy scattered radiation. Lead is typically used. Fluorescent screens are used in some situations to help reduce exposure times.

Image Quality. The quality level of an industrial radiograph is governed by the radiographic sensitivity exhibited on the radiograph itself. Radiographic sensitivity is determined through the use of penetrameters or image-quality indicators (IQI).

Penetrameters, or IQIs, are of known size and shape, and have the same attenuation characteristics as the material in the test piece. They are placed on the test piece or on a block of identical material during setup and are radiographed at the same time as the test piece. Penetrameters preferably are located in regions of maximum test-piece thickness and greatest test-piece-to-film distance, and near the outer edge of the central beam of radiation. The degree to which features of the penetrameter are visible in the developed image is a measure of the quality of that image. The image of the penetrameter that appears on the finished radiograph is evaluated during interpretation to ensure that the desired sensitivity, definition, and contrast have been achieved in the developed image.

Penetrameters of different designs have been developed by various standards-making organizations. Common types are plaques containing holes and a second type containing a series of wires. Plaque-type penetrameters consist of strips of material of uniform thickness with holes drilled through them specified by ASTM E 142. Wire-type penetrameters are widely used in Europe (see German standard DIN 54109). They are also used in the U.S. and are described in ASTM standard E 747. The sensitivity of a wire-type penetrameter is expressed in terms of wire diameter divided by object thickness.

Neutron Radiography

Neutron radiography is a form of nondestructive inspection that uses a specific type of particulate radiation, called neutrons, to form a radiographic image of a test piece. The geometric principles of shadow formation, variation of attenuation with test-piece thickness, and many other factors that govern the exposure and processing of a neutron radiograph are similar to those for radiography using x-rays or gamma rays.

The section deals mainly with the characteristics that differentiate neutron radiography from x-ray or gamma-ray radiography. The application of neutron radiography is described, especially in terms of its advantages for improved contrast on low-atomic-number materials, discrimination between isotopes, or inspection of radioactive specimens.

Neutrons are subatomic particles that are characterized by relatively large mass and a neutral electric charge. The attenuation of neutrons differs from the attenuation of x-rays in that the processes of attenuation are nuclear rather than processes that depend on interaction with electron shells surrounding the nucleus.

Neutrons are produced by nuclear reactors, accelerators, or certain radioactive isotopes, all of which emit neutrons of relatively high energy (fast neutrons). Because most neutron radiography is performed with neutrons of lower energy (thermal neutrons), the sources are usually surrounded by a "moderator," which is a material that reduces the kinetic energy of the neutrons by scattering.

Neutron radiography differs from conventional radiography in that the attenuation of neutrons as they pass through the test piece is more related to the specific isotope present than to density or atomic number. X-rays are attenuated more by elements of high atomic number than by elements of low atomic number, and this effect varies relatively smoothly with atomic number. Also, x-rays are generally attenuated more by materials of high density than they are by materials of low density. For thermal neutrons, the attenuation tends to decrease with increasing atomic number, although the trend is by no means a smooth relationship. In addition to the high attenuation of several light elements (hydrogen, lithium, and boron), certain medium to heavy elements (especially cadmium, samarium, europium, gadolinium, and dysprosium) and certain specific isotopes have exceptionally high capabilities for absorbing thermal neutrons. This means that neutron radiography is capable of detecting these highly attenuating elements or isotopes when present in a structure of lower absorption capability.

Using neutrons, it is possible to radiographically detect certain isotopes--for instance, certain isotopes of hydrogen, cadmium, or uranium. Some neutron-image-detection methods are insensitive to gamma rays or x-rays and can be used to inspect radioactive materials such as reactor fuel elements. The high attenuation of hydrogen, in particular, opens many application possibilities, including inspection of assemblies for detection of adhesives, explosives, lubricants, water, hydrides, corrosion, plastic, or rubber.

Neutron Sources

The excellent discrimination capabilities of neutrons generally refer to neutrons of low energy--that is, thermal neutrons. Characteristics of neutron radiography corresponding to various ranges of neutron energy are summarized in Table 8. Although any of these energy ranges can be used for radiography, this article emphasizes the thermal-neutron range, which is the most widely used for inspection.

Table 8 Characteristics of neutron radiography at various neutron-energy ranges

Type of neutrons	Energy range	Characteristics
Cold	Below 0.01 eV	High-absorption cross sections decrease transparency of most materials, but also increase efficiency of detection. An advantage is reduced scatter at energies below the Bragg cutoff, where neutrons can no longer undergo Bragg reflection.
Thermal	0.01 to 0.3 eV	Good discrimination between materials and ready availability of sources.
Epithermal	0.3 eV to 10 keV	Excellent discrimination for particular materials by working at energy of resonance. Greater transmission and less scatter in samples containing materials such as hydrogen and enriched reactor fuels.
Fast	10 keV to 20 MeV	Good point sources are available. At low-energy end of spectrum, fast-neutron radiography may be able to perform many inspections done with thermal neutrons, but with a panoramic technique. Good penetration capability because of low-absorption cross sections in all materials. Poor material discrimination

In thermal-neutron radiography, an object (test piece) is placed in a thermal-neutron beam in front of an image detector. The neutron beam may be obtained from a nuclear reactor, a radioactive source, or an accelerator. Several characteristics of these sources are summarized in Table 9. For thermal-neutron radiography, fast neutrons emitted by these sources must first be moderated and then collimated. The radiographic intensities listed in Table 9 typically do not exceed 10^{-5} times the total fast-neutron yield of the source. Part of this loss is incurred in moderating the neutrons, and the remainder in bringing a collimated beam out of a large-volume moderator.

Table 9 Several characteristics of thermal-neutron sources

Type of source	Typical radiographic intensity[(a)]	Resolution	Exposure time	Characteristics
Radioisotope	10^1-10^4	Poor to medium	Long	Stable operation, low to medium investment cost, possibly portable
Accelerator	10^3-10^6	Medium	Average	On-off operation, medium cost, possibly transportable
Subcritical assembly	10^4-10^6	Good	Average	Stable operation, medium to high investment cost, movement difficult
Nuclear reactor	10^5-10^8	Excellent	Short	Medium to high investment cost, movement difficult

(a) Neutrons per cm^2 per second

Collimation is necessary for thermal-neutron radiography because there are no useful point sources of low-energy neutrons. Good collimation in thermal-neutron radiography is comparable to small focal-spot size in conventional radiography; the images of thick objects will be sharper with good collimation. Conversely, it should be noted that available neutron intensity decreases with increasing collimation.

Neutron Detection Methods

Detection methods for neutron radiography generally make use of photographic or x-ray films. In the direct-exposure method, film is exposed directly to the neutron beam, with a conversion screen or intensifying screen providing secondary radiation that actually exposes the film. Alternatively, film can be used to record an autoradiographic image from a radioactive, image, carrying screen in a technique called the transfer method.

Direct-Exposure Method. Conversion screens of thin gadolinium foil or a scintillator have been most widely used in the direct-exposure method. When bombarded with a beam of neutrons, some of the gadolinium atoms absorb neutrons and promptly emit gamma rays and internal conversion electrons. Scintillators are fluorescent screens, often made of zinc sulfide crystals that also contain a specific isotope such as ${}_3Li^6$ or ${}_5B^{10}$. Gadolinium oxysulfide, a scintillator originally developed for x-ray radiography, has been widely used for neutron radiography.

Scintillators provide useful images with total exposures as low as 5×10^5 neutrons per cm^2. The high speed and favorable relative response make scintillators attractive for use with nonreactor neutron sources. Gadolinium screens provide greater uniformity and image sharpness (high-contrast resolution of 10 μm has been reported), but an exposure about 30 or more times that of a scintillator is required, even with fast films.

Transfer Method. In the transfer method, a thin sheet of metal, typically of indium or dysprosium, is exposed to the neutron beam transmitted through the specimen. Neutron capture induces radioactivity--indium having a half-life of 54 min and dysprosium a half-life of 2.35 h. The "radiograph" to be interpreted is made by placing the radioactive transfer screen in contact with a sheet of film. Beta-particles and gamma-rays from the transfer screen expose the film.

The transfer method is especially valuable for inspection of a radioactive specimen. Although radiation emitted by the specimen (especially gamma rays) causes heavy film fogging during x-ray radiography or direct-exposure neutron radiography, the same radiation will not induce radioactivity in a transfer screen. Thus, a clear image of the specimen can be obtained even when there is a high level of background radiation.

In comparing the two primary detection methods, the direct-exposure method offers high speed, indefinite image-integration time and the best spatial resolution. The transfer method offers insensitivity to gamma rays emitted by the specimen and greater contrast because of lower amounts of scattered and secondary radiation.

Real-time imaging, in which light from a scintillator is observed by a television camera, also can be used for neutron radiography. Because of low brightness, most real-time neutron radiographic images are enhanced by an image-intensifier tube, which may be separate or integral with a television camera. This method can be used for applications such as the study of fluid flow in a closed system such as a heat pipe or engine or the study of metal flow in a mold during casting.

Applications

Various applications that are discussed in ASTM STP 586 emphasize the value of neutron radiography for inspection of ordnance, explosive, aerospace, and nuclear components. The presence, absence, or correct placement of explosives, adhesives, O-rings, plastic components, and similar materials can be verified. The presence of fluids or corrosion can be detected. Nuclear fuel and control materials can be inspected to determine distribution of isotopes and to detect foreign or imperfect material. Hydride deposition in metals and diffusion of boron in heat treated boron-fiber composites can be observed.

The characteristics of neutron radiography complement those of conventional x-radiography; one radiation provides a capability lacking or difficult for the other.

Thermal Inspection

Introduction

THERMAL INSPECTION comprises inspection by all methods in which heat-sensing devices or substances are used to detect irregular temperatures. Thermal inspection of workpieces can be used to detect flaws and to detect undesirable distribution of heat during service. There are several methods of thermal inspection and many types of temperature-measuring devices and substances. This article, however, is limited mainly to the discussion of:

- Thermography, which is the mapping of isotherms, or contours of equal temperature, over a test surface
- Thermometry, which is the measurement of temperature.

These techniques are separated into two categories: (a) direct contact, in which a thermally sensitive device or material is placed in physical and thermal contact with the test piece; and (b) noncontact techniques that depend on thermally generated electromagnetic energy radiated from the test piece.

Contact Thermographic Inspection

Contact thermographic inspection consists of coating the surface of the test piece with a material that reacts to a change in temperature by changing color or other aspect of appearance. The reaction may be permanent or reversible. Many coatings having reversible reactions can be recovered for reuse.

The most commonly used materials for contact thermographic inspection can be classified as heat-sensitive paints, heat-sensitive papers, thermal phosphors, liquid crystals, and other temperature-sensitive coatings.

Material coatings are relatively low in cost and simple to apply, but they may have the disadvantage of providing qualitative temperature measurements (the exception is coatings with liquid crystals, which can be calibrated to show relatively small changes in temperature). Another disadvantage of coatings is that they may change the thermal characteristics of the surface.

Cholesteric liquid crystals are greaselike substances that can be blended to produce compounds having color transition ranges at temperatures from -20 to 250 °C (-5 to 480 °F). Liquid crystals can be selected to respond in a temperature range for a particular test and can have a color response for temperature differentials of 1 to 50 °C (2 to 90 °F). When illuminated with white light while in their color response range, liquid crystals will scatter the light into its component colors, producing an iridescent color that changes with the angle at which the crystals are viewed. Outside this color response range, liquid crystals are generally colorless. The response time for the color change varies from 30 to 100 ms. This is more than adequate to allow liquid crystals to show transient changes in temperature. The spatial resolution obtainable can be as small as 0.02 mm (0.0008 in.). In addition, because the color change is generally reversible, anomalies can be evaluated by repeating the test as many times as needed.

Techniques for applying liquid crystals are relatively straightforward once the proper blend of compounds is selected. Because liquid crystals function by reflecting light, they are more readily seen when used against a dark background. Therefore, if the specimen is not already dark, covering the surface with a removable, flat-black coating is strongly recommended before application. The crystals can then be applied by pouring, painting, spraying, or dipping. Care must be taken that the specimen or the coating is not attacked by the solvent base used with the liquid crystals. The applied film of liquid crystals must be of uniform thickness to prevent color irregularities caused by thickness differences rather than temperature differences. A good film thickness is about 0.02 mm (0.0008 in.). Successive layers used to build up the film thickness should not be allowed to dry between coats. A coating of proper thickness will have a uniform, low-gloss appearance when viewed with oblique illumination.

Thermally quenched phosphors are organic compounds that emit visible light when excited by ultraviolet light. The brightness of a phosphor is inversely proportional with temperature over a range from room temperature to about 400 °C (750 °F), as indicated in Fig. 1. Some phosphors exhibit a change in brightness of as much as 25%/°C (14%/°F). An individual phosphor should be selected to cover the temperature range used for a particular inspection. The coating is applied by painting a well-agitated mixture of the phosphor onto the surface to a thickness of about 0.12 mm (0.0047 in.).

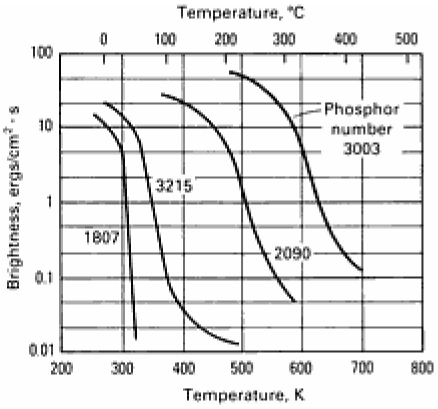


Fig. 1 Relative brightness of four thermally quenched phosphors (U.S. Radium Radelin phosphor numbers) as a function of temperature

Heat-sensitive paints that are effective from 40 to 1600 °C (about 100 to 2900 °F) are available. Some of these paints undergo several color transitions as their temperature is increased, and, under favorable conditions, an accuracy of ±5 °C

(±9 °F) is attainable with them. These paints have been used effectively for monitoring isotherms in heat-affected zones during welding, for monitoring preheating prior to welding, and for inspecting castings for porosity.

Heat-Sensitive Papers. Several types of heat-sensitive papers have been used in nondestructive inspection. They are applied by bonding directly to the surface of the test piece, or by means of a vacuum holddown arrangement.

One type consists of a porous paper coated with an organic compound. A finely divided white pigment is applied to a highly absorptive black paper in a binder soluble in a solvent that does not dissolve the pigment. When the melting temperature of the pigment is reached, the paper absorbs the coating and the initial white color is replaced by a black appearance. These papers are used to indicate when a specific temperature has been reached.

Noncontact Thermographic Inspection

A large number of devices will respond to the radiant energy in the infrared bandwidth produced by an object at a temperature above absolute zero and convert it to a proportional electric signal that then may be displayed. Infrared imaging equipment is available with a wide range of capabilities. The simplest systems are responsive to the near-infrared portion of the optical spectrum. These include night-vision devices and vidicon systems with silicon or lead sulfide sensors. Silicon sensors provide sensitivity for temperatures above 425 °C (800 °F), while lead sulfide sensors respond to temperatures above 200 °C (400 °F).

There are two basic types of infrared detectors: photon-effect devices and thermal devices. The response of the photon-effect devices depends on the wavelength of the received radiation; therefore, the output signal depends on the wavelength of the infrared signal. Thermal detectors respond only to the heating caused by the incoming radiation, and the output signal is largely independent of the radiation wavelength. At certain wavelengths, the photon-effect devices will produce a much larger signal than thermal detectors.

Hand-held infrared scanners are portable imaging systems capable of responding in the far-infrared portion of the optical spectrum (wavelengths of 8 to 12 μm). This range is emitted by objects at or near room temperature. In general, hand-held scanners have poor imaging qualities and are not suitable for the accurate measurement of local temperature differences. However, they can be useful for detecting hot spots, such as over-heated components, thermal runaway in an electronic circuit, or unextinguished fires.

High-resolution infrared imaging systems are required for most part inspection applications. These systems use either pyroelectric vidicon cameras with image-processing circuitry or cryogenically cooled mechanical scanners to provide good-quality image resolution (150 pixels, or picture elements, per scan line) temperature sensitivity to 0.1 °C (0.2 °F). In addition to good image resolution and temperature sensitivity, response times of the order of 0.1 s or less facilitate the detection of transient temperature changes or differentials. These imaging systems will use either a gray scale or a color scale correlated to temperature ranges to depict the temperature distribution within the image.

Thermal wave interferometer systems combine modulated laser excitation with rapid phase and amplitude sensing that can be scanned across a surface to produce an image. One application for this type of system is the inspection of plasma-sprayed coatings. The system senses the interaction between the thermal waves of the laser and the thermal variations from coating defects and thickness variations.

Contact Thermometric Inspection

There are several basic thermal detectors: bolometers, thermistors, thermocouples, and thermopiles. For the most part, they can be used either in direct contact with the test item or as radiation detectors (noncontact applications). These devices can detect infrared radiation of both short and long wavelengths, and very low-temperature or low-radiation levels without cryogenic cooling.

Bolometers are thermal detectors that are based on the principle that the resistance of a material changes as it is heated. The bolometer allows the radiation to impinge on a very fine wire or a thin metallic film, blackened to increase absorption. The change in resistance is then a direct function of the radiation absorbed. The temperature coefficient of a bolometer is from 0.3 to 0.5%/°C.

Thermocouples. A thermocouple consists of a junction of two dissimilar metals. As the junction temperature is raised, a thermoelectric electromotive force is produced. Thermocouples are always used in pairs in a bridge circuit so that the measured temperature is a direct function of the electromotive force produced by the sensing thermocouple as subtracted from the electromotive force produced by a reference thermocouple held at a known temperature.

Thermopiles. A thermopile is merely a series of thermocouple junctions; it produces an increase in electromotive force as a direct function of the number of junctions.

Meltable Substances. Waxlike crayons that melt at temperatures in the range of 38 to 1760 °C (100 to 3200 °F) are commercially available. Such a crayon has a melting point within a nominal tolerance of ±1% of its rated temperature value. These crayons are normally used by making a mark with one or more of them on a surface before it is heated.

Noncontact Thermometric Inspection

The temperature-measuring devices used in noncontact thermometric inspection depend on response of a thermal detector to infrared radiation. They are particularly useful when it is necessary to monitor or measure surface temperatures remotely.

Radiometers are instruments used to measure incident radiation. They consist of some type of hollow cavity with an aperture in one end and a thermal detector mounted internally. The thermal detector is so located that the radiation is focused on it. Because thermal detectors have a uniform response without regard to infrared wavelength, a radiometer is often used to measure total radiation. If the radiometer has a lens system, it will be restricted to the infrared-transmission characteristics of the lenses.

Pyrometers (or infrared thermometers) are used in nondestructive testing in much the same way as are infrared scanning devices. These instruments have less accuracy than other scanning devices, but they are simpler, more rugged, more portable, and less expensive. A wide variety of this type of equipment is commercially available, with a corresponding variety of performance.

Applicability

Thermal methods can be useful in the detection of subsurface flaws or voids, provided the depth of the flaw is not large compared to its diameter. Thermal inspection becomes less effective in the detection of subsurface flaws as the thickness of an object increases because the possible depth of the defects increases.

Thermal inspection is applicable to complex shapes or assemblies of similar or dissimilar materials and can be used in the one-sided inspection of objects. Moreover, because of the availability of infrared sensing systems, thermal inspection can also provide rapid, noncontact scanning of surfaces, components, or assemblies.

Thermal inspection does not include those methods that use thermal excitation of a test object and a nonthermal sensing device for inspection. For example, thermally induced strain in holography or the technique of thermal excitation with ultrasonic or acoustic methods does not constitute thermal inspection.

Holography

Introduction

HOLOGRAPHY is basically a two-step process for creating a whole image--that is, a three-dimensional image--of a diffusely reflecting object having some arbitrary shape. In the first step, both the amplitude and phase of any type of coherent wave motion emanating from the object are recorded by encoding this information in a suitable medium. This recording is called a hologram. At a later time, the wave motion is reconstructed from the hologram by a coherent beam in a process that results in the regeneration of an image having the true shape of the object. The utility of holography for nondestructive inspection of metal components and metal-containing structures lies in the fact that this regenerated image can then be used as a kind of three-dimensional template against which any deviations in the shape or dimensions of the object can be observed and measured.

In principle, holography can be performed with (a) any wave radiation encompassed in the entire electromagnetic spectrum, (b) any particulate radiation, such as neutrons and electrons, that possesses wave-equivalent properties; and (c) nonelectromagnetic wave radiation, such as sound waves. The two methods currently available for practical nondestructive inspection are optical holography, using visible light waves, and acoustical holography, using ultrasonic waves.

Optical Holography

Optical holographic interferometry has been successfully used both in research and testing applications as a noncontacting tool for displacement, strain and vibration studies, depth-contour mappings, and transient/dynamic phenomena analyses. Specific applications of optical holography in nondestructive evaluation include:

- Detection of debonds within honeycomb-core sandwich structures
- Detection of unbonded regions within pneumatic tires and other laminates
- Detection of cracks in hydraulic fittings
- Qualitative evaluation of turbine blades

Applicability

The advantages of using optical holographic interferometry for nondestructive inspection include the following:

- It can be applied to any type of solid material--ferromagnetic or nonferromagnetic; metallic, nonmetallic, or composite; electrically or thermally conductive or nonconductive; and optically transparent or opaque
- It can be applied to test objects of almost any size and shape, provided a suitable mechanism exists for stressing or otherwise exciting the object.
- Pulsed-laser techniques allow the inspection of test objects in unstable or hostile environments.
- It has an inherent sensitivity to the displacement or deformation of at least one-half an optical wavelength, or about 125 nm (1250 Å). This permits the use of low levels of stress during inspection. Further, special analysis techniques can provide improved sensitivity of almost 1000 fold.
- It does not rely on data acquisition by either point-by-point determinations or scanning processes; instead, three-dimensional images of interference fringe fields are obtained of the entire surface (front, back, and internal, if desired) or a large fraction thereof.
- It allows flexibility of readout. For example, in flaw detection applications, the images can be examined purely qualitatively for localized fringe anomalies within the overall fringe field. If, conversely, the application involves the strain analysis of an object subjected to a specific type of stress, the image can be analyzed to yield a highly quantitative point-by-point map of the resulting surface displacements.
- It permits comparison of the responses of an object to two different levels of stress or other excitation. The frame of reference for this differential measurement is usually, but not always, the unstressed or natural state of the test object. This differential type of measurement contrasts with absolute types, which are made without a frame of reference, and with comparative measurements, in which a similar but different object is used as a frame of reference.
- The interferograms can be reconstructed at any later time to produce three-dimensional replicas of the previously recorded test results.

The disadvantages of using optical holographic interferometry for nondestructive inspection include the following:

- Although no physical contact with the test object is required to effect the interaction of the coherent light with either the test object or the photographic plate, it is often necessary to provide fixturing not only for the test object but also for the stressing source. The success of a holographic inspection procedure depends largely on the adequacy of design and the practical performance of both the fixturing and the stress-imparting mechanisms.
- It is limited to test objects with wall or component thicknesses that will offer sufficiently large

displacements without requiring stressing forces that will cause rigid-body movement or damage to the object. For sandwich structures, the thickness of the skin is the limiting factor; the maximum skin thickness that can be tested is a function of the stressing method.

- Holographic methods are best suited to diffusely reflecting surfaces with high reflectivity. Removable coatings are often sprayed onto strongly absorbing materials and specularly reflecting surfaces
- Although holographic interferometry is capable of accurately locating a flaw within the surface area of the test object being inspected, the cross-sectional size of the flaw can often be only approximately determined, and information concerning the depth of the flaw, when obtainable at all, is qualitative in nature.
- Where visual interpretation of interferograms is to be performed, holographic interferometry may be limited in its dynamic range for some applications. However, electronic methods for fringe interpretation have been used to provide increased sensitivity and dynamic range.
- Test results sometimes cannot be analyzed because of the localization of the interference fringes in space rather than on the surface of the test object (in real-time holographic interferometry) or on the reconstructed image of the object (in double-exposure holographic interferometry).
- With the exception of holographic-contouring applications, holographic interferometry is currently limited to differential tests, in which the object is compared to itself after it has been subjected to changes in applied stress. Comparative tests, in which a given object can be compared to a standard object, are not feasible with holographic interferometry because of inherent random variations in test object surfaces.
- Personnel performing holographic inspection must be properly trained. The greater the sophistication of the equipment, the greater the required operating skill.

Optical Holography Method

Holographic Recording. When visible lightwaves are used, the hologram is recorded with an optical system called a holocamera (see Fig. 1a). A monochromatic laser beam of phase-coherent light is divided into two beams by a variable beam splitter. One beam, the object beam, is expanded by a spatial filter into a divergent beam directed to illuminate the object uniformly. A portion of the laser light reflected from the object is intercepted by a high-resolution photographic plate, as shown in Fig. 1(a). The second beam, the reference beam, originating from the beam splitter is directed by a mirror, diverges from a second spatial filter, and is directed onto the photographic plate by a second mirror. With either object beam or reference beam absent, a uniformly exposed photographic plate will result. However, with both coherent beams falling on the plate simultaneously, an interference pattern is generated as a result of the coherent interaction of the two beams, and this pattern is recorded by the photographic emulsion.

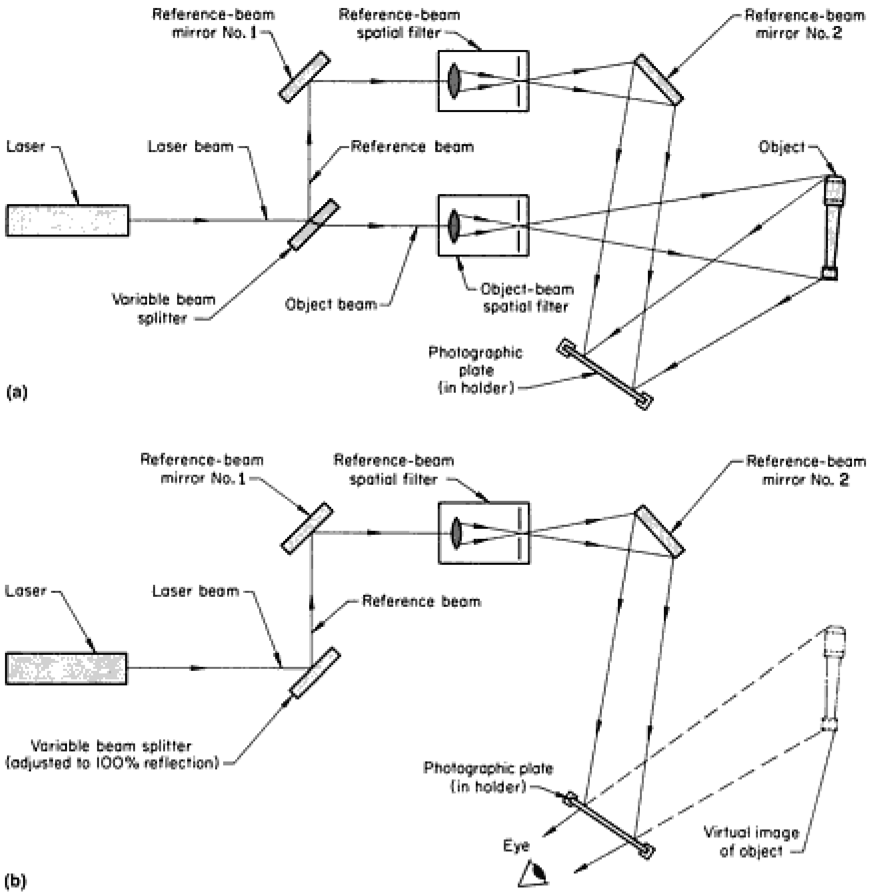

Reference-beam mirror No. 1
Reference-beam spatial filter
Reference-beam mirror No. 2
Laser
Laser beam
Reference beam
Object
Variable beam splitter
Object beam
Object-beam spatial filter
Photographic plate (in holder)
(a)
Reference-beam mirror No. 1
Reference-beam spatial filter
Reference-beam mirror No. 2
Laser
Laser beam
Reference beam
Variable beam splitter (adjusted to 100% reflection)
Photographic plate (in holder)
Eye
Virtual image of object
(b)

Fig. 1 Schematic diagrams of the basic optical systems used in continuous-wave holography: (a) holocamera used to record hologram of an object on a photographic plate and (b) optical system for reconstructing a virtual image of the object from the hologram on the photographic plate

Holographic Reconstruction. In the reconstruction process, which is illustrated in Fig. 1(b), the hologram is used as a diffraction grating. When it is illuminated with the reference beam only, three beams emerge--a zero-order, or undeflected, beam and two first-order diffracted beams. The diffracted beams produce the real and virtual images of the object to complete the holographic process. The real image is pseudoscopic, or depth inverted, in appearance. Hence, the virtual image (also referred to as the true, primary, or nonpseudoscopic image) is the image that is of primary interest in practical applications of holography. In Fig. 1(b), only the first-order diffracted beam that yields the virtual image is shown, the other two beams having been omitted from the figure for the sake of clarity. If the original object is three-dimensional, the virtual image is a genuine three-dimensional replica of the object, possessing both parallax and depth of focus. However, if the configuration of the optical system or the wavelength of light used during reconstruction differs from that used during recording, distortion, aberration, and changes in magnification can occur. (The holographic recording and reconstruction systems can be designed to minimize these effects.)

Interferometric Techniques of Inspection. When optical holography is applied to inspection of parts, generation of a three-dimensional image of the object, per se, is of little value. Furthermore, for opaque materials, optical holography is strictly limited to surface observations. Hence, if optical holography is to be used for nondestructive inspection, supplementary means must be used to either stress or otherwise excite test objects to produce surface manifestations of the feature of interest. It is for measurement of such manifestations that the techniques of optical holography have been further developed to form the subfield of holography termed optical holographic interferometry.

As in conventional interferometry, holographic interferometric measurements can be made with great accuracy (to within a fraction of the wavelength of the light being used). Whereas conventional interferometry is usually restricted to the examination of objects having highly polished surfaces and simple shapes, holographic interferometry can be used to examine objects of arbitrary shape and surface condition. Because holographic interferometry produces a three-dimensional fringe-field image, which can be examined from many different perspectives (limited only by the size of the hologram), a single holographic interferogram is equivalent to a series of conventional two-dimensional interferograms.

In contrast to conventional interferometry, which must be performed in real time, holographic interferometry can be performed either in real time or at two different times (time-lapse technique). In the time-lapse technique, advantage is taken of the fact that more than one hologram may be made on the same recording medium. Examples of this approach include the double-exposure, multiple-exposure, and continuous-exposure techniques.

Acoustical Holography

Acoustical holography is the extension of holography into the ultrasonic domain. The principles of acoustical holography are the same as those of optical holography because the laws of interference and diffraction apply to all forms of radiation obeying the wave equation. Differences arise only because the methods for recording and reconstructing the hologram must accommodate the form of radiation used. This need to accommodate the form of radiation restricts the practical range of sound-wave frequency that can be used in acoustical holography.

At present, only two types of basic systems for acoustical holography are available--the liquid-surface type and the scanning type. These utilize two different detection methods, and these methods in turn dictate the application of the systems to nondestructive inspection. Neither of these two types of systems relies on the interferometric techniques of optical holographic inspection, where information on flaws at or near the surface of a test object is obtained from the pattern formed by interference between two nearly identical holographic images that are created while the object is differentially stressed. Instead, systems for acoustical holography obtain information on internal flaws directly from the image of the interior of the object.

Liquid-Surface Acoustical Holography. The basic system for liquid-surface acoustical holography is similar to the basic system for optical holography, except for the method of read out.

In liquid-surface systems, two separate ultrasonic transducers supply the object beam and reference beam, which are usually pulsed. The two transducers and the test object are immersed in a water-filled tank. The test object is positioned in the object plane of an acoustic (ultrasonic) lens, which also is immersed in the tank.

The practical limits for the object-beam transducer in a commercial system are a wave frequency of 1 to 10 MHz, a pulse length of 50 to 300 microseconds, and a pulse-repetition rate of 60 to 100 per second. This transducer is placed so that its beam passes through the test object. As the object beam passes through the test object, it is modified by the object. The modification is generally in both amplitude and phase. The object beam then passes through an acoustic lens, which focuses the image of the test object at the liquid surface. This image contains a wave front nearly identical to that emanating from the test object.

The reference-beam transducer is connected to the same oscillator as the object-beam transducer so that it emits a second wave front coherent with the wave front from the object-beam transducer. The reference-beam transducer is aimed at the same region of the liquid surface as the object beam, where the wave fronts interfere. The image is reconstructed from the hologram by reflecting a beam of coherent light from the ripple pattern in the isolation tank.

Scanning Acoustical Holography. The basic system for scanning acoustical holography is shown in Fig. 2. No reference-beam transducer is required in this system because electronic phase detection is used to produce the hologram: that is, the required interaction (mixing) between the piezoelectrically detected object-beam signal and the simulated reference-beam signal occurs in the electronic domain. A pulser circuit--consisting of a continuous-wave oscillator and a pulse gate that is triggered by an electronic clock--and a power amplifier feed a single focused ultrasonic transducer that is scanned over an area above the test object while alternately transmitting and receiving the ultrasonic signals. The transducer and the test object are immersed in a water-filled tank, as in Fig. 2(b), or they are coupled by a water column.

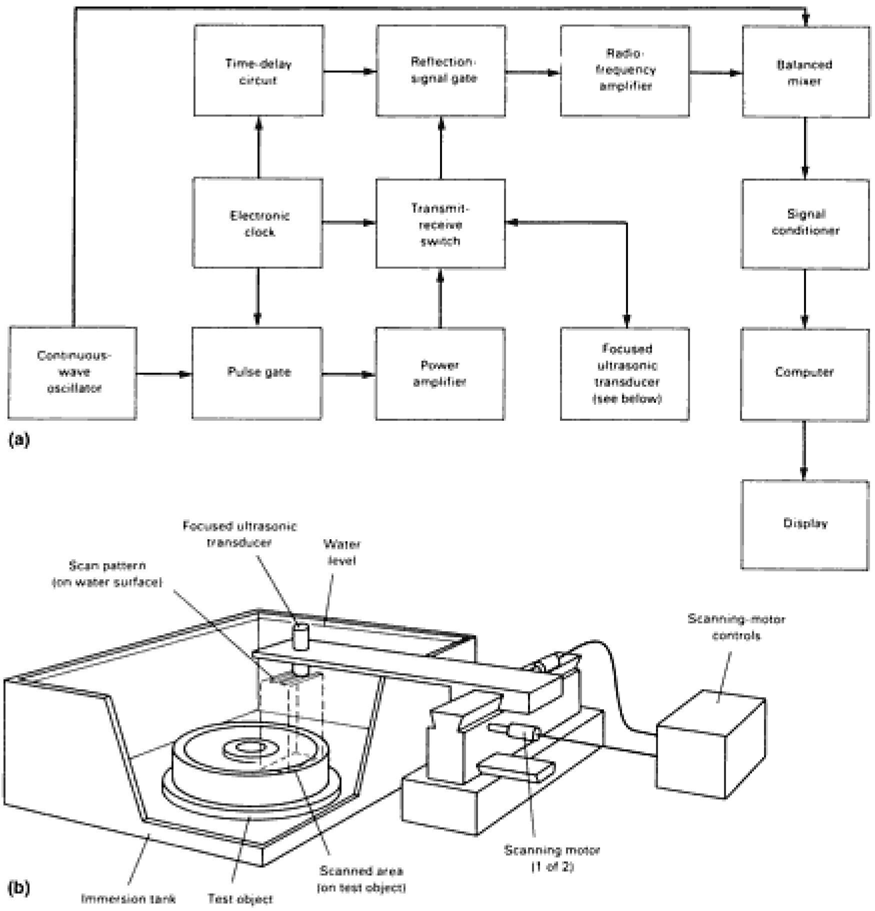

Time-delay circuit
Reflection-signal gate
Radio-frequency amplifier
Balanced mixer
Electronic clock
Transmit-receive switch
Signal conditioner
Continuous-wave oscillator
Pulse gate
Power amplifier
Focused ultrasonic transducer (see below)
Computer
(a)
Display
Focused ultrasonic transducer
Water level
Scan pattern (on water surface)
Scanning-motor controls
Scanning motor (1 of 2)
Scanned area (on test object)
(b)
Immersion tank
Test object

Fig. 2 Diagrams of the basic system used in nondestructive inspection by scanning acoustical holography. See text for description. (a) Ultrasonic and light portions of systems. (b) Scanning and recording portions of system

The signal is pulsed so that time gating can be used to reject undesired surface echoes. The pulse length may be set to any desired value from a few periods of the wave frequency to an upper limit of 50% of the time between successive pulses. Long pulse lengths are used to examine regions lying deep within the metal, while short pulse lengths are required for the regions near the surface so that transmitted energy is not mixed with reflected energy. The practical limits of the transducer in a commercial system are a wave frequency of 1 to 10 MHz, a pulse length of 5 to 20 microseconds, and a pulse-repetition rate of 500 to 1000 per second. The frequency band of a given transducer is relatively narrow (±5% of the mean frequency).

The echo from the flaw is received by the transducer and processed by a time-interval counter or a pair of balanced mixers in quadrature. The resulting data are digitized and entered into the computer. As the transducer scans a rectangular area, a matrix of complex numbers accumulates in the computer. This matrix represents the phase and amplitude of the reflected wave taken on a set of sample points.

Comparison of Liquid-Surface and Scanning Systems. The outstanding feature of the liquid-surface system of acoustical holography is that it provides a real-time image, whereas the image provided by the scanning system requires reconstruction. The real-time feature makes the liquid-surface system suitable for rapid inspection of large amounts of material on a continuous basis. In contrast, inspection with the scanning system is relatively slow. Photographic or videotape records for later study may be made with either system.

The outstanding feature of the scanning system is its ability to determine accurately the position and dimensions of flaws lying deep in opaque test objects, especially when only one side of the object is accessible. (In contrast to the scanning system, the liquid-surface system is usually operated in the transmission mode, which requires access to both sides of the test object.) Although both systems offer about the same resolution, the sensitivity of the scanning system is greater by a factor of about 10^6. The excellent flaw-measuring ability of the scanning system can be used to characterize accurately the flaws detected previously by faster inspection methods, such as scanning with a conventional ultrasonic search unit.

Another important feature of the scanning system is that the commercial equipment for this system is usually transportable, whereas liquid-surface equipment is usually stationary. In addition, scanning transducers can be coupled to very large test objects by water columns, whereas inspection by the liquid-surface system usually requires that the test objects be small enough to be placed in a water-filled tank and completely immersed.

A useful advantage of the scanning system is its capability of selectively producing either longitudinal or shear waves in the volume of metal under examination, by adjustment of the angle of incidence of the incoming ultrasonic beam.

Mechanical Testing

Hardness Testing

HARDNESS is a term that has different meanings to different people: it is resistance to penetration to a metallurgist, resistance to wear to a lubrication engineer, a measure of flow stress to a design engineer, resistance to scratching to a mineralogist, and resistance to cutting to a machinist. Although these various definitions of hardness appear to differ significantly in character, they are all related to the plastic flow stress of the material.

Table 1 lists the major types of hardness testers, which can be either portable instruments or laboratory devices. Only static indentation and rebound testing are discussed in this article. These two methods account for virtually all routine hardness testing in the metalworking industry. Static indentation hardness testing is the more widely used of the two methods, although rebound testing is extensively employed, particularly for hardness measurements on large workpieces or for applications in which visible or sharp impressions in the test surface cannot be tolerated.

Table 1 Classification of hardness testers

Method	Type
Indentation: standard operation	
Vickers	Macroindentation or microindentation
Rockwell	Macroindentation
Brinell	Macroindentation
Indentation: nonstandard operation	
Rockwell	Low-load
Vickers	Low-load
Brinell	Calibrated pin system (static or dynamic)
Indentation: equivalent hardness	
Static	"Press-and-read" type (mechanical or electronic)
	"Scissors" type
	Clamp type
Dynamic	Cylinder type
Other indentation methods	
UCI method	. . .
Comparative hardness method	Cylinder type
	Horizontal bar type
Dynamic	
Reaction force	Piezo-electric crystal principle
Rebound	Mechanical
	Electronic (EQUO) method

Source: P.F. Aplin, Classification and Solution of Portable Hardness-Testing Equipment, *Non-Destructive Testing,* Vol 1, Elsevier

Brinell Hardness Testing

The Brinell hardness test is basically simple, and it consists of applying a constant load, usually 500 to 3000 kg, on a hardened steel ball-type indenter, 10 mm in diameter, to the flat surface of a workpiece (Fig. 1). The 500 kg load is usually used for testing nonferrous metals, such as copper and aluminum alloys, whereas the 3000 kg load is most often used for testing harder metals, such as steels and cast irons. The load is held for a specified time (10 to 15 s for iron or steel and about 30 s for softer metals), after which the diameter of the recovered indentation is measured in millimeters. This time period is required to ensure that plastic flow of the work metal has stopped.

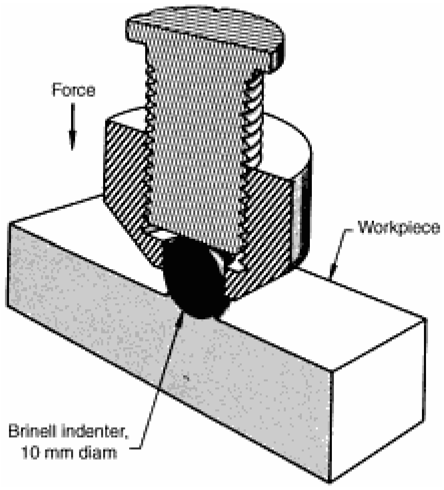


Fig. 1 Sectional view of a Brinell indenter, showing the manner in which the application of force by the indenter causes the metal of the workpiece to flow

Hardness is evaluated by taking the mean diameter of the indentation (two readings at right angles to each other) and calculating the Brinell hardness number (HB) by dividing the applied load by the surface area of the indentation according to the following formula:

$$\text{HB} = L/(\pi D/2)[D - (D^2 - d^2)^{1/2}]$$

where L is the load, in kilograms; D is the diameter of the ball, in millimeters; and d is the diameter of the indentation, in millimeters.

It is not necessary, however, to make the calculation for each test. Such calculations are available in table form for all diameters of indentations in Section 1 of this Handbook.

Highly hardened steel (or other very hard metals) cannot be tested by a hardened steel ball by the Brinell method, because the ball will flatten during penetration and a permanent deformation will take place. This problem is recognized in specifications for the Brinell tests.

Tungsten carbide balls are recommended for Brinell testing materials of hardness from 444 HB up to about 627 HB (indentation of 2.45 mm in diameter). However, higher Brinell values will result when using carbide balls instead of steel balls because of the difference in elastic properties.

Surface Preparation. The degree of accuracy that can be attained by the Brinell hardness test can be greatly influenced by the surface smoothness of the workpiece being tested.

The surface of the workpiece on which the Brinell indentation is to be made must be filed, ground, machined, or polished with emery paper (3/0 emery paper is suitable) so that the indentation diameter is clearly enough defined to permit its measurement. There should be no interference from tool marks.

Indentation Measurement. The diameter of the indentation is measured by a microscope to the nearest 0.05 mm (0.002 in.). This microscope contains a scale, and usually a built-in light, to facilitate easy reading.

The indentations produced in Brinell hardness tests may exhibit different surface characteristics. These have been carefully studied and analyzed. In some instances there is a ridge around the indentation extending above the original surface of the workpiece. In other instances the edge of the indentation is below the original surface. Sometimes there is no difference at all. The first phenomenon is called a "ridging" type of indentation and the second a "sinking" type. Cold worked metals generally have the former type of indentation, and annealed metals the latter type.

Brinell Hardness Testers. Several types of testers that exert the prescribed force on the indenter are in general use. The two general types are hydraulic analog testers and newer digital hardness testers. Digital hardness testers have better resolution than analog testers. The resolution of digital testers reduces or eliminates the need for extrapolation, but they are not as durable as analog testers.

In statistical process control of Brinell testing, there is no adequate way to achieve high process capability indices (C_p and C_{pk} values) without making the investment in state of the art optics that utilize frame grabbers to read the impression. It is possible to take several impressions on pieces and take the average of these impressions to get a point in a subgroup, but this method requires larger sample sizes and inspection costs increase.

Many analog Brinell testers are typically manually operated hydraulic instruments like the one show in Fig. 2. The workpiece is placed on the anvil and raised, by means of the elevating screw, to a position near the indenter. Fingertip rotation of the control knob allows a selected force (in kilograms), indicated on the gage, to be applied. This force is held for a pre-established length of time and then released. The specimen is removed and the indentation measured. The entire cycle, including indenting and measurement, requires approximately one minute.

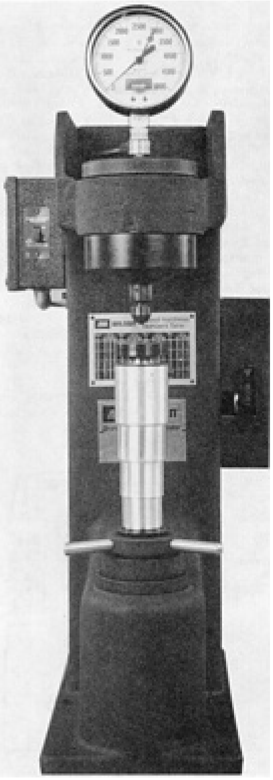


Fig. 2 Analog Brinell hardness tester

Portable Brinell Hardness Testers. Conventional Brinell hardness testers have limited use, for two reasons: (a) the workpieces to be tested must be brought to the testers, and (b) size and design of the workpieces must be such that they can be placed between the anvil and the indenter.

Some of the problems posed by these limitations can often be solved by use of a portable hardness tester. Hydraulic portable testers like the general design shown in Fig. 3 weigh no more than about 25 lb and can be easily transported to the workpieces. Smaller, digital testers are also available.

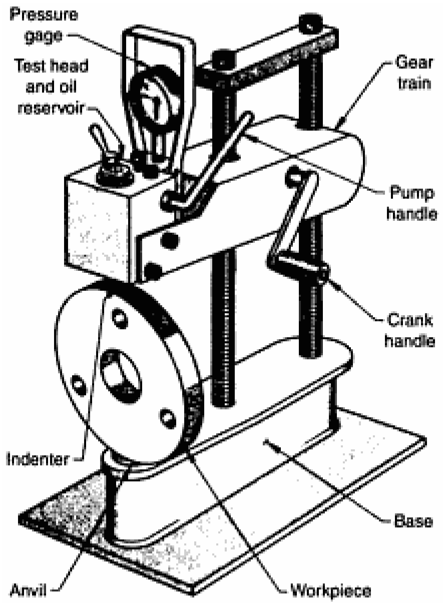


Fig. 3 Hydraulic, manually operated portable Brinell hardness tester

Spacing of Indentations. To ensure accurate results, indentations should not be made too close to the edge of the workpiece being tested. Lack of sufficient supporting material on one side of the workpiece will cause the resulting indentation to be large and unsymmetrical. It is generally agreed that the error in a Brinell hardness number is negligible if the distance from the center of the indentation is not less than $2\frac{1}{2}$ times (and preferably 3 times) the diameter of the indentation from any edge of the workpiece.

Similarly, indentations should not be made too close to one another. If indentations are too close together, the work metal may be cold worked by the first indentation, or there may not be sufficient supporting material for the second indentation. The latter condition would produce too large an indentation, whereas the former may produce too small an indentation. To prevent this, the distance between centers of adjacent indentations should be at least three times the diameter of the indentation.

General Precautions. To avoid misapplication of Brinell hardness testing, the fundamentals and limitations of the test procedure must be clearly understood. Further, to avoid inaccuracies, some general rules should be followed. Such rules include the following:

1. Indentations should not be made on a curved surface having a radius of less than 1 in.
2. Spacing of indentations should be correct, as outlined above under "Spacing of Indentations."
3. The load should be applied steadily to avoid overloading caused by inertia of the weights.
4. The load should be applied in such a way that the direction of loading and the test surface are perpendicular to each other within 2°.
5. The thickness of the workpiece being tested should be such that no bulge or mark showing the effect of the load appears on the side of the workpiece opposite the indentation. In any event, the thickness of the specimen shall be at least ten times the depth of indentation.
6. The surface finish of the workpiece being tested should be such that the indentation diameter is clearly outlined.

Limitations. The Brinell hardness test has three principal limitations:

1. Size and shape of the workpiece must be capable of accommodating the relatively large indentations.
2. Because of the relatively large indentations, the workpiece may not be usable after testing.

3. The limit of hardness range--about 11 HB with the 500 kg load to 627 HB with the 3000 kg load--is generally considered the practical range.

Rockwell Hardness Testing

Rockwell hardness testing is the most widely used method for determining hardness. There are several reasons for this distinction. The Rockwell test is simple to perform and does not require highly skilled operators. By use of different loads and indenters, Rockwell hardness testing can be used for determining hardness of most metals and alloys, ranging from the softest bearing materials to the hardest steels. A reading can be taken in a matter of seconds with conventional manual operation and in even less time with automated setups. No optical measurements are required (all readings are direct).

Rockwell hardness testing differs from Brinell hardness testing in that the hardness is determined by the depth of indentation made by a constant load impressed upon an indenter. Although a number of different indenters are use for Rockwell hardness testing, the most common type is a diamond ground to a 120° cone with a spherical apex having a 0.2 mm radius, which is known as a Brale indenter (Fig. 4a).

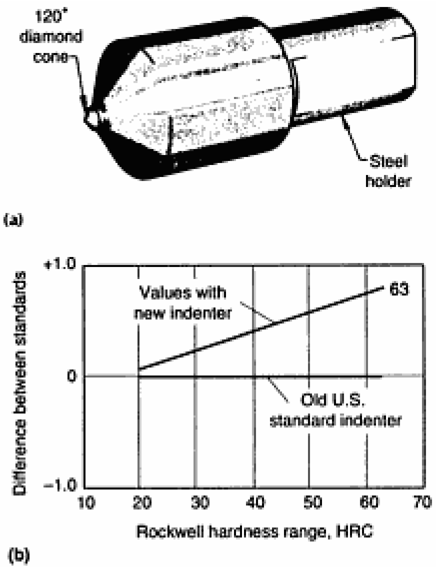


Fig. 4 Rockwell indenter. (a) Diamond-cone Brale indenter (show at about 2×). (b) Comparison of old and new U.S. diamond indenters. The angle of the new indenter remains at 120° but has a larger radius closer to the average ASTM specified value of 200 μm; the old indenter has a radius of 192 μm. The indenter with the larger radius has a greater resistance to penetration of the surface.

The shape of the Rockwell diamond indenter most widely used in the United States is different from indenters in the rest of the world. The ASTM specification calls for a diamond cone radius of 200 ± 10 μm (0.0079 in.), but in practice, it is closer to 192 μm (0.0076 in.). While not out of tolerance, the old U.S. standard indenter is at the low end of the specification. In the United States, the diamond was first set at 192 μm to match the nominal values of the hardness test blocks. However, the rest of the world has used a diamond size closer to 200 μm (0.0079 in.).

A comparison of the old (192 μm) U.S. standard diamond indenter and the current (200 μm tip) U.S. indenter is shown in Fig. 4(b). The larger radius increases the indenter's resistance to penetration into the surface of the testpiece.

At higher HRC hardness, most of the indenter travel is along the radius; whereas at the lower hardnesses, more indenter travel is along the angle. This is why the hardness shift from old to new has been most significant in the HRC 63 range and not the HRC 25 range.

Methods

As shown in Fig. 5, the Rockwell hardness test consists of measuring the additional depth to which an indenter is forced by a heavy (major) load (Fig. 5b) beyond the depth of a previously applied light (minor) load (Fig. 5a). Application of the minor load eliminates backlash in the load train and causes the indenter to break through slight surface roughness and to crush particles of foreign matter, thus contributing to much greater accuracy in the test. The basic principle involving minor and major loads illustrated in Fig. 5 applies to steel-ball indenters as well as to diamond indenters.

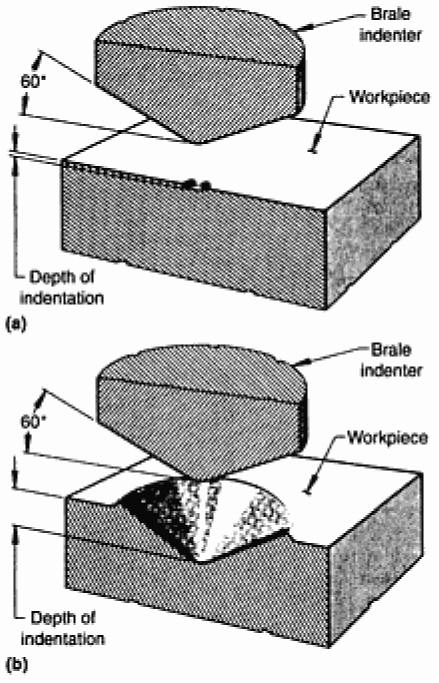


Fig. 5 Indentation in a workpiece made by application of (a) the minor load, and (b) the major load, on a diamond Brale indenter in Rockwell hardness testing. The hardness value is based on the difference in depths of indentation produced by the minor and major loads.

The minor load is applied first, and a reference or "set" position is established on the measuring device of the Rockwell hardness tester. Then the major load is applied at a prescribed, controlled rate. Without moving the workpiece being tested, the major load is removed and the Rockwell hardness number is automatically indicated on the dial gage. The entire operation takes from 5 to 10 s.

Diamond indenters are used mainly for testing materials, such as hardened steels and cemented carbides. Steel-ball indenters available with diameters of $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, and $\frac{1}{2}$ in., are used for testing materials, such as soft steel, copper alloys, aluminum alloys, and bearing metals.

Rockwell Testers. There are two basic types of Rockwell hardness testers--regular and superficial. Both testers have similar basic mechanical principles and significant components.

Rockwell testers generally come with two different resolutions. The standard Rockwell analog tester (Fig. 6), which has been the industrial workhorse for years, has a resolution of 1.0 HRC. Many operators think they can improve resolution to 0.5 HRC or even 0.1 HRC by extrapolation, but this is not true. Extrapolation of readings only increases measurement error when several operators are checking parts.

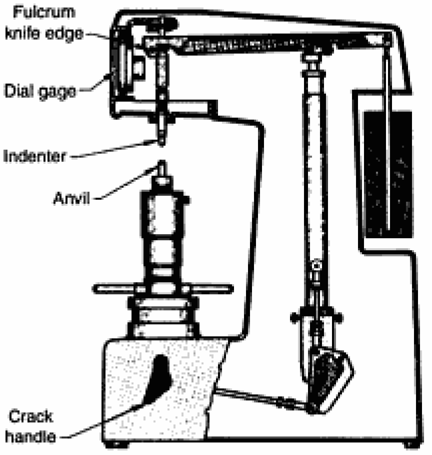


Fig. 6 Principal components of a regular (normal) Rockwell hardness tester. Superficial Rockwell testers are similarly constructed.

As with Brinell testing, better resolution can be achieved by investing in digital testing equipment. The newer digital Rockwell testers (Fig. 7) have a resolution of 0.1 HRC, and they eliminate the need for extrapolation (guessing). Similar resolution can be obtained on portable digital testers.

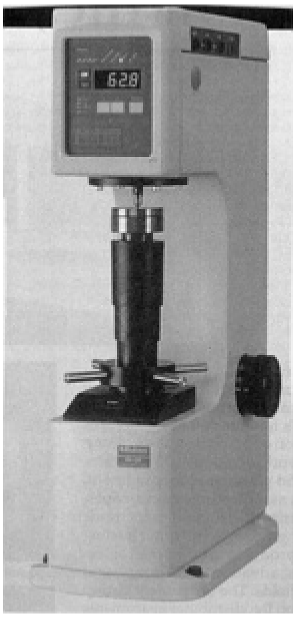


Fig. 7 A digital Rockwell hardness tester

Regular Rockwell Hardness Testing. In regular Rockwell hardness testing, the minor load is always 10 kg. The major load, however, can be 60, 100, or 150 kg. No Rockwell hardness value is expressed by a number alone. A letter has been assigned to each combination of load and indenter, as shown in Table 2. Each number is suffixed by first the letter H (for hardness), then the letter R (for Rockwell), and finally the letter that indicates the scale used. For example, a value of 60 on the Rockwell C scale is expressed as 60 HRC, and so on. Regardless of the scale used, the "set" position is the same; however, when the diamond Brale indenter is used, the readings are taken from the black divisions on the dial gage. When testing with any of the ball indenters, the readings are taken from the red divisions.

Table 2 Rockwell-hardness-scale designations for combinations of type of indenter and major load

Scale designation	Indenter		Major load, kg	Dial figure
	Type	**Diam, in.**		
Regular Rockwell tester				
B	Ball	$\frac{1}{16}$	100	Red
C	Brale	. . .	150	Black
A	Brale	. . .	60	Black
D	Brale	. . .	100	Black
E	Ball	$\frac{1}{8}$	100	Red
F	Ball	$\frac{1}{16}$	60	Red
G	Ball	$\frac{1}{16}$	150	Red
H	Ball	$\frac{1}{8}$	60	Red
K	Ball	$\frac{1}{8}$	150	Red
L	Ball	$\frac{1}{4}$	60	Red
M	Ball	$\frac{1}{4}$	100	Red
P	Ball	$\frac{1}{4}$	150	Red
R	Ball	$\frac{1}{2}$	60	Red
S	Ball	$\frac{1}{2}$	100	Red
V	Ball	$\frac{1}{2}$	150	Red
Superficial Rockwell Tester				
15N	N Brale	. . .	15	. . .
30N	N Brale	. . .	30	. . .
45N	Brale	. . .	45	. . .
15T	Ball	$\frac{1}{16}$	15	. . .
30T	Ball	$\frac{1}{16}$	30	. . .
45T	Ball	$\frac{1}{16}$	45	. . .
15W	Ball	$\frac{1}{8}$	15	. . .
30W	Ball	$\frac{1}{8}$	30	. . .
45W	Ball	$\frac{1}{8}$	45	. . .
15X	Ball	$\frac{1}{4}$	15	. . .
30X	Ball	$\frac{1}{4}$	30	. . .
45X	Ball	$\frac{1}{4}$	45	. . .
15Y	Ball	$\frac{1}{2}$	15	. . .
30Y	Ball	$\frac{1}{2}$	30	. . .
45Y	Ball	$\frac{1}{2}$	45	. . .

One Rockwell number represents an indentation of 0.002 mm (0.00008 in.). Therefore, a reading of 60 HRC indicates indentation from minor to major load of (100 - 60) × 0.002 mm = 0.080 mm, or 0.0032 in. A reading of 80 HRB indicates an indentation of (130 - 80) × 0.002 mm = 0.100 mm, or 0.004 in.

Superficial Rockwell hardness testing employs a minor load of 3 kg, but the major load can be 15, 30, or 45 kg.

Just as in regular Rockwell testing, the indenter may be either a diamond or a steel ball, depending mainly on the nature of the metal being tested. Regardless of load, the letter N designates use of the superficial Brale, and the letters T, W, X, and Y designate use of steel-ball indenters. Scale and load combinations are presented in Table 2. Superficial Rockwell hardness values are always expressed with the number suffixed by a number and a letter that show the load/indenter combination. For example, if a load of 30 kg is used with a diamond indenter and a reading of 80 is obtained, the result is reported as 80 HR30N (where H means hardness, R means Rockwell, 30 means a load of 30 kg, and N indicates use of a diamond indenter).

All tests are started from the "set" position. One Rockwell superficial hardness number represents an indentation of 0.001 mm or 0.00004 in. Therefore, a reading of 80 HR30N indicates indentation from minor to major load of (100 - 80) × 0.001 mm = 0.020 mm, or 0.0008 in.

Dials on the superficial hardness testers contain only one set of divisions, which is used with all types of superficial indenters.

Selection of Rockwell Scale

Where no specification exists or there is doubt abut the suitability of a specified scale, an analysis should be made of those factors that influence the selection of the proper scale. These influencing factors are found in the following four broad categories:

- Type of work metal
- Thickness of work metal
- Width of area to be tested
- Scale limitation

Influence of Type of Work Metal. The types of work metal normally tested using the different regular Rockwell hardness scales are given in Table 3. This information also can be helpful when one of the superficial Rockwell scales may be required. For example, note that the C, A, and D scales--all with diamond indenters--are used on hard materials, such as steel and tungsten carbide. Any material in this hardness category would be tested with a diamond indenter. The choice to be made is whether the C, A, D, or the 45N, 30N, or 15N scale is applicable. Whatever the choice, the number of possible scales has been reduced to six. The next step is to find a scale, either regular or superficial, that will guarantee accuracy, sensitivity, and repeatability of testing.

Table 3 Typical applications of regular Rockwell hardness scales

Scale(a)	Typical applications
B	Copper alloys, soft steels, aluminum alloys, malleable iron
C	Steel, hard cast irons, pearlitic malleable iron, titanium, deep case-hardened steel, and other materials harder than 100 HRB
A	Cemented carbides, thin steel, and shallow case-hardened steel
D	Thin steel and medium case-hardened steel and pearlitic malleable iron
E	Cast iron, aluminum and magnesium alloys, bearing metals
F	Annealed copper alloys, thin soft sheet metals
G	Phosphor bronze, beryllium copper, malleable irons. Upper limit is 92 HRG to avoid flattening of ball.
H	Aluminum, zinc, lead
K, L, M, P, R, S, V	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that do not give anvil effect.

(a) The N scales of a superficial hardness tester are used for materials similar to those tested on the Rockwell C, A, and D scales but of thinner gage or case depth. The T scales are used for materials similar to those tested on the Rockwell B, F, and G scales but of thinner gage. When minute indentations are required, a superficial hardness tester should be used. The W, X, and Y scales are used for very soft materials

Influence of Thickness of Work Metal. The metal immediately surrounding the indentation in a Rockwell hardness test is cold worked, The depth of material affected during testing is on the order of ten times the depth of the indentation. Therefore, unless the thickness of the metal being tested is at least ten times the depth of the indentation, an accurate Rockwell hardness test cannot be expected.

The depth of indentation for any Rockwell hardness test can easily be computed; in practice, however, computation is not necessary, because tables of minimum thicknesses are available (for example, see Table 4). The values for minimum thickness do follow the 10-to-1 ratio in some ranges, but they are actually based on experimental data accumulated on various thicknesses of low-carbon steels and of steel strip that has been hardened and tempered.

Table 4 Minimum work-metal hardness values for testing various thicknesses of metals with regular and superficial Rockwell hardness testers

Metal thickness, in.	Minimum hardness for superficial hardness testing						Minimum hardness for regular hardness testing					
	Diamond Brale indenter			**Ball indenter, $\frac{1}{16}$ in.**			**Diamond Brale indenter**			**Ball indenter, $\frac{1}{16}$ in.**		
	15N (15 kg)	**30N (30 kg)**	**45N (45 kg)**	**15T (15 kg)**	**30T (30 kg)**	**45T (45 kg)**	**A (60 kg)**	**D (100 kg)**	**C (150 kg)**	**F (60 kg)**	**B (100 kg)**	**G (150 kg)**
0.005	. . .	. . .	. . .	93	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.006	92	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.008	90	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.010	88	. . .	. . .	90	87	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.012	83	82	77	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.014	76	80	74	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
0.015	. . .	. . .	. . .	78	77	77	. . .	. . .	. . .	. . .	. . .	. . .
0.016	68	74	72	. . .	. . .	. . .	86	. . .	. . .	. . .	. . .	. . .
0.018	(a)	66	68	. . .	. . .	. . .	84	. . .	. . .	. . .	. . .	. . .
0.020	(a)	57	63	(a)	58	62	82	77	. . .	100	. . .	. . .
0.022	(a)	47	58	. . .	. . .	. . .	78	75	69	. . .	. . .	. . .
0.024	(a)	(a)	51	. . .	. . .	. . .	76	72	67	. . .	. . .	. . .
0.025	. . .	. . .	. . .	(a)	(a)	26	. . .	. . .	. . .	92	92	90
0.026	(a)	(a)	37	. . .	. . .	. . .	71	68	65	. . .	. . .	. . .
0.028	(a)	(a)	20	. . .	. . .	. . .	67	63	62	. . .	. . .	. . .
0.030	(a)	(a)	(a)	(a)	(a)	(a)	60	58	57	67	68	69
0.032	(a)	(a)	(a)	. . .	. . .	. . .	(a)	51	52	. . .	. . .	. . .
0.034	(a)	(a)	(a)	. . .	. . .	. . .	(a)	43	45	. . .	. . .	. . .
0.035	. . .	. . .	. . .	(a)	(a)	(a)	. . .	. . .	. . .	(a)	44	46
0.036	(a)	(a)	(a)	. . .	. . .	. . .	(a)	(a)	37	. . .	. . .	. . .
0.038	(a)	(a)	(a)	. . .	. . .	. . .	(a)	(a)	28	. . .	. . .	. . .
0.040	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	20	(a)	20	22

These values are approximate only and are intended primarily as a guide: see test for example of use. Materials thinner than shown may be tested on a Tukon microhardness tester. The thickness of the workpiece should be at least $1\frac{1}{2}$ times the diagonal of the indentation when using a Vickers indenter, and at least $\frac{1}{2}$ times the long diagonal when using a Knoop indenter.

(a) No minimum hardness for metal of equal or greater thickness.

To use the values in Table 4, assume that it is necessary to check the hardness of a strip of steel 0.014 in. thick, of an approximate hardness of 63 HRC. According to Table 4, material having a hardness of 63 HRC must be approximately 0.028 in. thick for an accurate test using the C scale. Therefore, this steel strip should not be tested on the C scale. At this point, check the approximate converted hardness on the other Rockwell scales equivalent to 63 HRC. These values taken from a conversion table are 83 HRA, 70 HR45N, 80 HR30N, and 91 HR15N. Referring again to Table 4 for hardened 0.014 in. thick material, there are only three Rockwell scales to choose: 45N, 30N, and 15N. The 45N scale is not suitable because the material should be at least 74 HR45N. On the 30N scale, 0.014 in. thick material must be at least 80 HR30N, and the material at hand is 80 HR30N. On the 15N scale, the material must be at least 76 HR15N, and this material is 91.5 HR15N. Therefore, either the 30N or 15N scale may be used. After all limiting factors have been eliminated, and a choice exists between two or more scales, the scale applying the heavier load should be used. The heavier load will produce a larger indentation, covering a greater portion of the material, and a Rockwell hardness number more representative of the material as a whole will be obtained. In addition, the heavier the load, the greater the sensitivity of the scale. Checking any conversion table and comparing the 15N scale to the 30N scale will show that in the hard-steel range a difference in hardness of one point on the 30N scale represents a difference of only 0.5 point on the 15N scale. Therefore, smaller differences in hardness can be detected when using the 30N scale.

This approach would also apply in determining which scale should be used to measure the hardness of a case of known approximate depth and hardness.

Influence of Test-Area Width. In addition to the limitation of indentation depth for a workpiece of given thickness and hardness, there is a limiting factor on the minimum width of material. If the indentation is placed too close to the edge of a workpiece, the edge will deform outward and the Rockwell hardness number will be decreased accordingly.

Experience has shown that the distance from the center of the indentation to the edge of the workpiece must be at least $2\frac{1}{2}$ times the diameter of the indentation to ensure an accurate test. Therefore, the width of a narrow test area must be at least five indentation diameters when the indentation is placed in the center.

Limitations of Rockwell Scales. The potential range of each Rockwell scale can be determined readily from the dial-gage divisions on the tester: the black scale (for diamond indenter) on all regular hardness-tester dial gages is numbered from 0 to 100, with 100 corresponding to the "set" position; the red scale (for ball indenters) is numbered from 0 to 130, with 130 being the "set" position. On the superficial hardness tester, the dial gage has only one set of divisions, numbered from 0 to 100.

Use of the diamond indenter when readings fall below 20 is not recommended, because there is loss of sensitivity when indenting this far down the conical section of the indenter. Brale indenters are not calibrated below values of 20; and if used on soft materials, there is no assurance that there will be the usual degree of agreement in results when replacing the indenters.

Support for Workpiece. A fundamental requirement of the Rockwell hardness test is that the surface of the workpiece being tested be approximately normal to the indenter and that the workpiece must not move or slip in the slightest degree as the major load is applied. The depth of indentation is measured by the movement of the plunger rod holding the indenter; therefore, any slipping or moving of the workpiece will be followed by the plunger rod and the motion transferred to the dial gage, causing an error to be introduced into the hardness test. As one point of hardness represents a depth of only 0.00008 in., a movement of only 0.001 in., could cause an error of over 10 Rockwell numbers. The support must be of sufficient rigidity to prevent its permanent deformation in use.

Standardized Hardness Values

In 1990, after several meetings between the American Society for Testing and Materials (ASTM) and standards groups from Europe and Asia, the U.S. government agreed to provide hardness standards for U.S. manufacturers. The reason for the change is that hardness, though based on traceable parameters, has had no absolute numbers. For example, the loads on a tester can be verified with a traceable load cell, but the hardness values themselves are empirical. The result is a value that is not directly traceable to any standard, national or otherwise. In the future, the values will be absolute, and will be traceable to a government standard.

The hardness program at the National Institute of Standards and Technology (NIST) involves traceable Standard Reference Materials (SRMs) blocks. The hardness standards are to be calibrated at NIST by means of a dead weight tester. Only two of these machines exist in the world. Other primary machines exist in other countries, but the only exact duplicate of the NIST machine is located at IMGC, which is the NIST equivalent in Italy.

The new NIST traceable blocks, at a nominal size of 60 mm (2.36 in.) diam and 15 mm (0.6 in.) thick, are larger than the typical Rockwell hardness test blocks. They are made of steel in the appropriate HRC range and have a polished mirror-like surface. Although most ASTM type HRC Rockwell test blocks are labeled ±0.5 HRC on the high end (60 HRC range), the NIST blocks will have much tighter tolerances (down to 0.1). Test locations will be indicated on the block; associated hardness numbers and statistical information will be listed on the certificate, enabling the user to find more than the just arithmetic mean of the hardness.

The very first blocks for Rockwell tests will be Hardness Rockwell C (HRC). The blocks should appear for sale in the near future. However, it is possible that not all the Rockwell scales will be represented. Which scales are needed will be decided by the scientists at NIST.

Vickers Hardness Testing

In 1925, Smith and Sandland of the United Kingdom developed a new indentation test for metals that were too hard to evaluate by the Brinell test, whose hardened steel ball was limited to steels with hardnesses below ~450 HBS (~48 HRC). In designing the new indenter, they chose a square-based diamond pyramid (Fig. 8) geometry that would produce hardness numbers nearly identical to Brinell numbers within the range of both. This decision was very wise, as it made the Vickers test very easy to adopt.

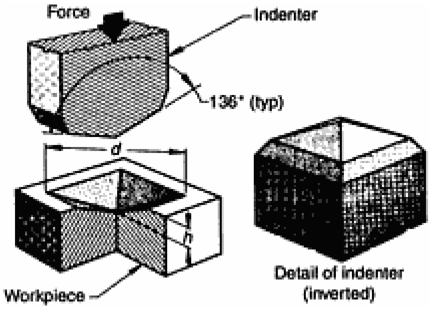


Fig. 8 Schematic representation of the square-base pyramidal diamond indenter used in a Vickers hardness tester and the resulting indentation in the workpiece

The ideal d/D ratio (d = impression diameter, D = ball diameter) for a spherical indenter is 0.375. If tangents are drawn to the ball at the impression edges for $d/D = 0.375$, they meet below the center of the impression at an angle of 136°, the angle chosen for the Vickers indenter.

The use of a diamond indenter allows the Vickers test to evaluate any material and, furthermore, has the very important advantage of placing the hardness of all materials on one continuous scale. The lack of a continuous scale is a major disadvantage of Rockwell type tests, for which 15 standard and 15 superficial scales were developed. Not one of these scales can cover the full hardness range. The HRA scale covers the broadest hardness range, but it is not commonly used.

In the Vickers test, the load is applied smoothly, without impact, and held in place for 10 or 15 s. The physical quality of the indenter and the accuracy of the applied load (defined in ASTM E 384) must be controlled to get the correct results. After the load is removed, the two impression diagonals are measured, usually with a filar micrometer, to the nearest 0.1 μm, and then averaged. The Vickers hardness (HV) is calculated by:

$$\mathrm{HV} = 1854.4L/d^2$$

where the load L is in grams-force, and the average diagonal d is in μm (although the hardness number units are expressed in units of kgf/mm^2 rather than the equivalent gf/μm^2).

The original Vickers testers were developed for test loads of 1 to 120 kgf, which produce rather large indents. Recognizing the need for lower test loads, the National Physical Laboratory (U.K.) experimented with lower test loads in 1932. The first low-load Vickers tester was described by Lips and Sack in 1936.

Because the shape of the Vickers indentation is geometrically similar at all test loads, the HV value is constant, within statistical precision, over a very wide test load range, as long as the test specimen is reasonably homogeneous. However, studies of microindentation hardness test results conducted over the, past several years on a wide range of loads have shown that results are not constant at very low loads. This problem, called the "indentation size effect" (ISE), has been attributed to fundamental characteristics of the material. In fact, the same effect is observed at the low-load test range of bulk Vickers testers.

Procedure. As noted, the Vickers hardness test follows the Brinell principle, in that an indenter of definite shape is pressed into the material to be tested, the load removed, and the diagonals of the resulting indentation measured. The indenter is made of diamond and is in the form of a square-base pyramid having an angle of 136° between faces (Fig. 8). This indenter has angle across corners, or so-called edge angle, of 148° 6' 42.5". The facets are highly polished and free from surface imperfections, and the point is sharp. The loads applied vary from 1 to 120 kg; the standard loads are 5, 10, 20, 30, 50, 100, and 120 kg. For most hardness testing, 50 kg is maximum.

With the Vickers indenter, the depth of indentation is about one-seventh of the diagonal length of the indentation. For certain types of investigation, there are advantages to such a shape. The Vickers hardness number (HV) is the ratio of the load applied to the indenter to the surface area of the indentation. By formula:

$$\mathrm{HV} = 2P \sin(\theta/2)/d^2$$

where P is the applied load, in kilograms; d is the mean diagonal of the indentation, in millimeters; and θ is the angle between opposite faces of the diamond indenter (136°).

Equipment for determining the Vickers hardness number should be designed to apply the load without impact, and friction should be reduced to a minimum. The actual load on the indenter should be correct to less than 1%, and the load should be applied slowly, because the Vickers is a static test. Some standards require that the full load be maintained for 10 to 15 s.

To obtain the greatest accuracy in hardness testing, the applied load should be as large as possible, consistent with the dimensions of the workpiece. Loads of more than 50 kg are likely to fracture the diamond, especially when used on hard materials.

The accuracy of the micrometer microscope should be checked against a stage micrometer, which consists of ruled lines, usually 0.1 mm apart, that have been checked against certified length standards. The average length of the two diagonals is used in determining the hardness value.

The comers of the indentation provide indicators of the length of the diagonals. The area must be calculated from the average of readings of both diagonals. The indentations are usually measured under vertical illumination with a magnification of about 125 diameters.

The included angle of the diamond indenter should be 136° with a tolerance of less than ±0.50°, which is readily obtainable with modem diamond-grinding equipment. This would mean an error of less than 1% in the hardness number. The indenters must be carefully controlled during manufacture so that in use the indentations produced will be symmetrical. Tables are available for converting the values of the diagonals of indentation in millimeters to the Vickers hardness number.

Vickers Hardness Testers. Several types of Vickers hardness testers are available. The principal component of a basic Vickers tester is shown schematically in Fig. 9(a). A modern Vickers tester is shown in Fig. 9(b). Current equipment may include image analysis peripherals and other features for more automated handling and testing. Automation methods include motorized stage capabilities where long or repetitive hardness traverses are required. These can be programmed so that little operator involvement is required during the indentation mode. Digital display of the measured diagonals and automatic calculation of the hardness from the diagonals also simplify measurement but still require the operator to peer into the microscope portion of the tester. Some systems include a closed circuit television system to the tester so that the operator can look at the magnified image on the TV screen and measure the diagonals. This is easier on the operators, but resolution of the system may not be as high.

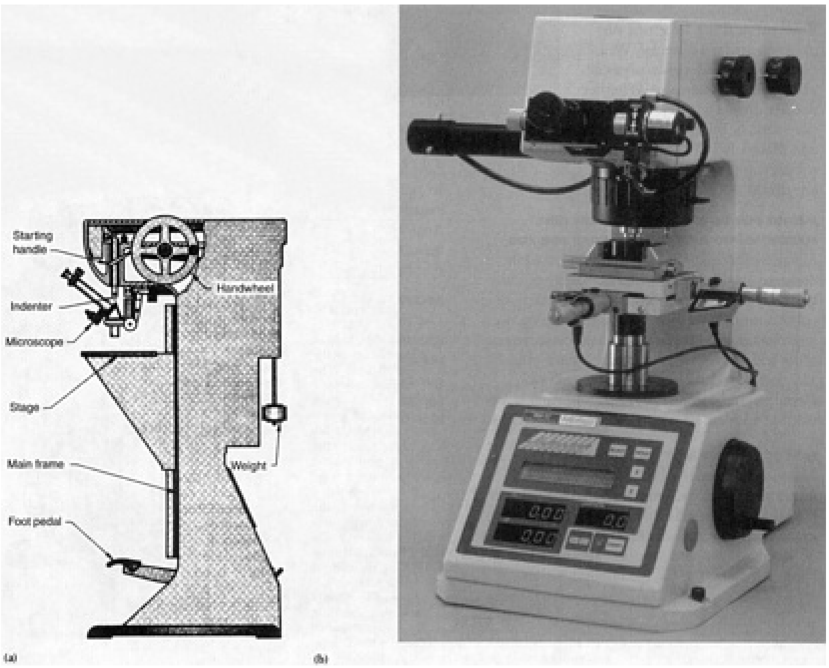
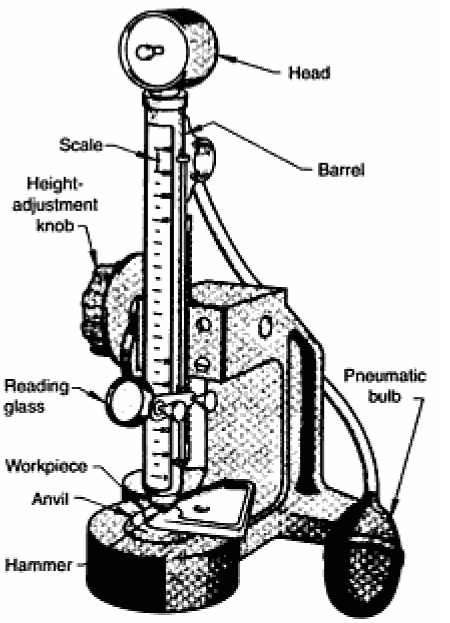


Fig. 9 Vickers hardness testers. (a) Principal components of a mechanical type. (b) Modern Vickers tester with digital readout of diagonal measurements and hardness values

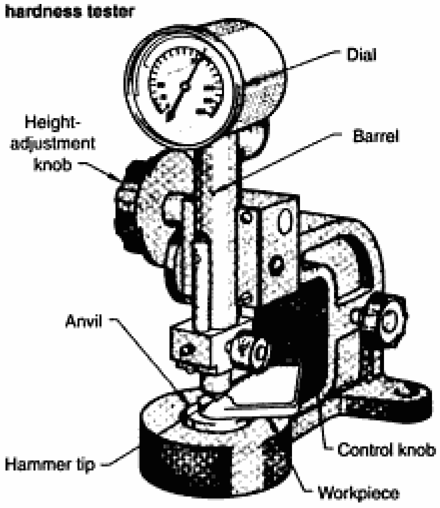
Scleroscope Hardness Testing

The Scleroscope hardness test is essentially a dynamic indentation hardness test, wherein a diamond-tipped hammer is dropped from a fixed height onto the surface of the material being tested. The height of rebound of the hammer is a measure of the hardness of the metal. The Scleroscope scale consists of units that are determined by dividing the average rebound of the hammer from a quenched (to maximum hardness) and untempered water-hardening tool steel into 100 units. The scale is continued above 100 to permit testing of materials having hardnesses greater than that of fully hardened tool steel.

Testers. Two types of Scleroscope hardness testers are shown in Fig. 10. The Model C Scleroscope consists of a vertically disposed barrel containing a precision-bore glass tube. A base-mounted version of a Model C Scleroscope is shown in Fig. 10(a). The scale is graduated from 0 to 140. It is set behind and is visible through the glass tube. Hardness is read from the vertical scale, usually with the aid of the reading glass attached to the tester, A pneumatic actuating head, affixed to the top of the barrel, is manually operated by a rubber bulb and tube. The hammer drops and rebounds with the glass tube.



(a) Model C (vertical scale) Scleroscope hardness tester



(b) Model D (dial reading) Scleroscope hardness tester

Fig. 10 Principal components of two types of base-mounted Scleroscope hardness testers

The Model D Scleroscope hardness tester (Fig. 10b) is a dial-reading tester. The tester consists of a vertically disposed barrel that contains a clutch to arrest the hammer at maximum height of rebound, which is made possible because of the short rebound height. The hammer is longer and heavier than the hammer in the Model C Scleroscope and develops the same striking energy while dropping a shorter distance.

Both models of the Scleroscope hardness tester may be mounted on various types of bases. The C-frame base, which rests on three points and is for bench use in hardness testing small workpieces, has a capacity about 3 in. high by $2\frac{1}{2}$ in. deep. A swing arm and post is also for bench use but has height and reach capacities of 9 and 14 in., respectively. Another type of base is used for mounting the Scleroscope hardness tester on rolls and other cylindrical objects having a minimum diameter of $2\frac{1}{2}$ in., or on flat, horizontal surfaces having a minimum dimension of 3 by 5 in. The Model C Scleroscope hardness tester is commonly used unmounted. However, when the hardness tester is unmounted, the workpiece should have a minimum weight of 5 lb. The Model D Scleroscope hardness tester should not be used unmounted.

Workpiece Surface-Finish Requirements. As with other metallurgical hardness testers, certain surface-finish requirements on the workpiece must be met for Scleroscope hardness testing to make an accurate hardness determination.

An excessively coarse surface finish will yield erratic readings. Hence, when necessary, the surface of the workpiece should be filed, machined, ground, or polished to permit accurate, consistent readings to be obtained.

Limitations on Workpiece and Case Thickness. Case-hardened steels having cases as thin as 0.010 in. can be accurately hardness tested provided the core hardness is no less than 30 Scleroscope. Softer cores require a minimum case thickness of 0.015 in. for accurate results.

Thin strip or sheet may be tested, with some limitations, but only when the Scleroscope hardness tester is mounted in the clamping stand. Ideally, the sheet should be flat and without undulation. If the sheet material is bowed, the concave side should be placed up to preclude any possibility of erroneous readings due to spring effect. The minimum thicknesses of sheet in various categories (in inches) that may be hardness tested are as follows:

Hardened steel	**0.005**
Cold finished steel strip	0.010
Annealed brass strip	0.015
Half-hard brass strip	0.010

Test Procedure. To perform a hardness test with either the Model C or the Model D Scleroscope hardness tester, the tester should be held or set in a vertical position, with the bottom of the barrel in firm contact with the workpiece. The hammer is raised to the elevated position and then allowed to fall and strike the surface of the workpiece. The height of rebound is then measured, which indicates the hardness. When using the Model C Scleroscope hardness tester, the hammer is raised to the elevated position by squeezing the pneumatic bulb. The hammer is released by again squeezing the bulb. When using the Model D Scleroscope hardness tester, the hammer is raised to the elevated position by turning the knurled control knob clockwise until a definite stop is reached. The hammer is allowed to strike the workpiece by releasing the control knob. The reading is recorded on the dial

Spacing of Indentations. Indentations should be at least 0.50 mm (0.020 in.) apart and only one at the same spot. Flat workpieces with parallel surfaces may be hardness tested within $\frac{1}{4}$ in. (6 mm) of the edge when properly clamped.

Taking the Readings. Experience is necessary to interpret the hardness readings accurately on a Model C Scleroscope hardness tester. Thin materials or those weighing less than 5 lb must be securely clamped to absorb the inertia of the hammer. The sound of the impact is an indication of the effectiveness of the clamping: a dull thud indicates that the workpiece has been clamped solid, whereas a hollow ringing sound indicates that the workpiece is not tightly clamped or is warped and not properly supported. Five hardness determinations should be made and their average taken as representative of the hardness of a particular workpiece.

Advantages of the Scleroscope hardness test are summarized as follows:

1. Tests can be made very rapidly. Over 1000 tests per hour are possible.
2. Operation is simple and does not require highly skilled technicians.
3. The Model C Scleroscope tester is portable and may be used unmounted for hardness testing workpieces of unlimited size: rolls, large dies, and machine-tool ways.
4. The Scleroscope hardness test is a nonmarring test; no crater is left, and only in the most unusual instances would the tiny hammer mark be objectionable on a finished workpiece.
5. A single scale accommodates the entire hardness range from the softest to the hardest metals.

Limitations of the Scleroscope hardness test are summarized as follows:

1. The hardness tester must be in a vertical position, or the free fall of the hammer will be impeded and result in erratic readings.
2. Scleroscope hardness tests are more sensitive to variations in surface conditions than some other hardness tests.

3. Because readings taken with the Model C Scleroscope hardness tester are those observed from the maximum rebound of the hammer on the first bounce, even the most experienced operators may disagree among themselves by one or two points in the reading.

Microhardness Testing

The term "microhardness" usually refers to indentation hardness tests made with loads not exceeding 1 kg. Such hardness tests have been made with a load as light as 1 g, although the majority of microhardness tests are made with loads of 100 to 500 g. In general, the term is related to the size of the indentation rather than the load applied.

Fields of Application

Microhardness testing is capable of providing information regarding the hardness characteristics of materials that cannot be obtained with hardness tests, such as the Brinell, Rockwell, or Scleroscope.

Because of the required degree of precision for both equipment and operation, microhardness testing is usually, although not necessarily, performed in a laboratory. Such a laboratory, however, is often a process-control laboratory and may be located close to production operations. Microhardness testing is recognized as a valuable method for controlling numerous production operations in addition to its use in research applications. Specific fields of application of microhardness testing include:

- Measuring hardness of precision workpieces that are too small to be measured by the more common hardness-testing methods
- Measuring hardness of product forms, such as foil or wire, that are too thin or too small in diameter to be measured by the more convenient methods
- Monitoring of carburizing or nitriding operations, which is usually accomplished by hardness surveys taken on cross sections of test pieces that accompanied the workpieces through production operations
- Measuring hardness of individual microconstituents
- Measuring hardness close to edges, thus detecting undesirable surface conditions, such as grinding bum and decarburization
- Measuring hardness of surface layers, such as plating or bonded layers

Indenters

Microhardness testing is performed with either the Knoop or the Vickers indenter. The Knoop indenter is more widely used in the United States; the Vickers indenter is more widely used in Europe.

Knoop indentation testing is performed with a diamond ground to pyramidal form that produces a diamond-shape indentation having an approximate ratio between long and short diagonals of 7 to 1 (Fig. 11). The pyramidal shape employed has an included longitudinal angle of 172° 30' and an included transverse angle of 130°. The depth of indentation is about one thirtieth of its length. Because of the shape of the indenter, indentations of accurately measurable lengths are obtained with light loads.

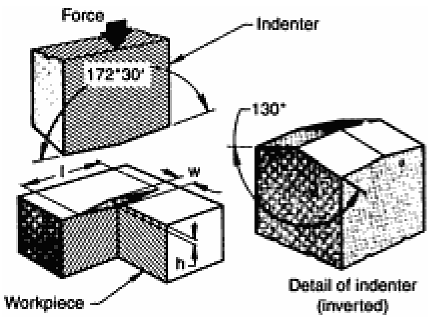


Fig. 11 Schematic representation of a pyramidal Knoop indenter and the resulting indentation in the workpiece

The Knoop hardness number (HK) is the ratio of the load applied to the indenter to the unrecovered projected area of indentation. By formula:

$$\text{HK} = P/A = P/CL^2$$

where P is the applied load, in kilograms; A is the unrecovered projected area of indentation, in square millimeters; L is the measured length of the long diagonal, in millimeters; and C is 0.07028, a constant of the indenter relating projected area of the indentation to the square of the length of the long diagonal.

Figure 12 presents a comparison of the indentations made by the Knoop and Vickers indenters. Each has some advantages over the other. For example, the Vickers indenter penetrates about twice as far into the workpiece as does the Knoop indenter, and the diagonal of the Vickers indentation is about one-third of the total length of the Knoop indentation. Therefore, the Vickers indenter is less sensitive to minute differences in surface conditions than is the Knoop indenter. However, the Vickers indentation, because of the shorter diagonal, is more sensitive to errors in measurement than is the Knoop indentation.

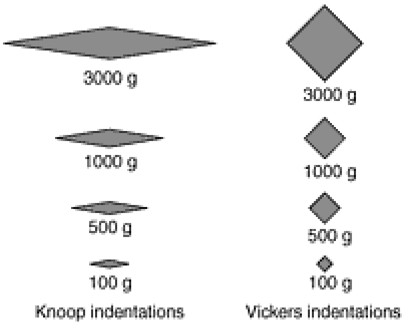


Fig. 12 Comparison of indentations made by Knoop and Vickers indenters in the same work metal and at the same loads

The shortcoming of the Knoop indent is that the three-dimensional indent shape changes with test load and, consequently, HK varies with load. In fact, HK values may be reliably converted to other test scales only for HK values produced at the standard load, generally 500 gf, that was used to develop the correlations. However, at high loads the variation is not substantial. Note that all hardness scale conversions are based on empirical data; consequently, conversions are not precise but are estimates.

Microhardness Testers

Several types of microhardness testers are available. The most accurate operate through the direct application of load by dead weight or by weights and lever.

The Tukon tester is widely used for microhardness testing. Several different designs of this microhardness tester are available; they vary mainly in load range, but all can accommodate both Knoop and Vickers indenters.

The Tukon microhardness tester shown in Fig. 13 has a load range of 1 to 1000 g. Loads are applied by dead weight. The microscope is furnished with three objective lenses having magnifications of about 150, 300, and 600 diameters.

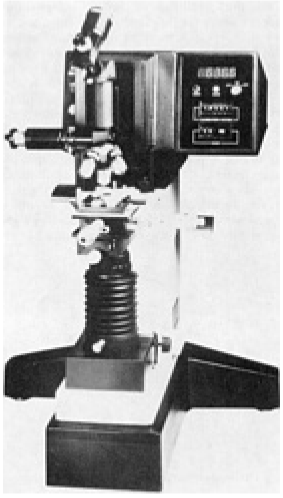


Fig. 13 Principal components of a Tukon microhardness tester

Sources of tester error include inaccuracy in loading, vibration, rate of load application, duration of contact period, and impact. To limit the shock that can occur when the operator removes the load (this generally has an adverse effect on indentations made with loads below 500 g), an automatic test cycle is built into the Tukon microhardness tester. With this automatic test cycle, the load is applied at a constant rate, maintained in the work for 18 s, and smoothly removed. Thus, the operator does not need to touch the tester while the load is being applied and removed. The design of microhardness testers will vary from one type to another, but it is essential to remove the applied load without touching the tester if clear-cut indentations are to be obtained.

A movable stage to support the workpiece is an essential component of a microhardness tester. In many applications the indentation must be in a selected area, usually limited to a few thousandths of a square millimeter. In testing with the type of Tukon microhardness tester shown in Fig. 13, first the required area is located by looking through the microscope and moving the mechanical stage until the desired location is centered within the optical field of view. The stage is then indexed under the indenter, and the automatic indentation cycle is initiated by tripping the handle. After the cycle is completed, signaled by a telltale light, the stage is again indexed back under the objective for indentation measurement.

Optical equipment used in microhardness testers for measuring the indentation must focus on both ends of the indentation at the same time, as well as be rigid and free from vibration. Lighting is also important. Complete specifications of measurement, including the mode of illumination, are necessary in microhardness-testing techniques. Polarized light, for instance, results in larger measurements than does unpolarized light. Apparently, this is caused by the reversal of the diffraction pattern; that is, the indentation appears brighter than the background. When test data are recorded, it is recommended that both the magnification and the type of illumination used be reported.

In measuring the indentation, the proper illumination to obtain optimum resolution is essential, and the appropriate objective lens should be selected. In operation, the ends of the indentation diagonals should be brought into sharp focus. With the Knoop indenter, one leg of the long diagonal should not be more than 20% longer than the other. If this is not apparent or if the ends of the diagonal are not in focus, the surface of the workpiece should be checked to make sure it is normal to the axis of the indenter. With the Vickers indenter, both diagonals should be measured and the average used for calculating the Vickers hardness number (HV).

Preparing and Holding the Specimen

Regardless of whether the metal being tested for microhardness is an actual workpiece or a representative specimen, surface finish is of prime importance.

To permit accurate measurement of the length of the Knoop indentation or diagonals of the Vickers indentation, the indentation must be clearly defined. In general, as the test load decreases, the surface-finish requirements become more stringent. When the load is 100 g or less, a metallographic finish is recommended.

Specific Applications of Microhardness Testing

Microhardness testing is used extensively in research and for controlling the quality of manufactured products, as well as for solving shop problems.

Testing of small workpieces is an important use of microhardness testing. Many manufactured products, notably in the instrument and electronics industries, are too small to be tested for hardness by the more conventional methods. Many such workpieces can be tested without impairing their usefulness, generally by means of various types of holding and clamping fixtures.

Microhardness testing is also applied to product forms that cannot be tested by other means. Thin foils and small-diameter wires are typical examples.

Monitoring of Surface-Hardening Operations. Microhardness testing is the best method in present use for accurately determining case depth and certain case conditions of carburized or nitrided workpieces, using the hardness-survey procedure. In most instances this is accomplished by use of test coupons that have accompanied the actual workpiece through the heat treating operation. The coupons are then sectioned and usually mounted for testing. To ensure accurate readings close to the edge of the cross section, the 100 g is most often used, although a 500 g load is sometimes preferred. If the 100 g load is used, a metallographic finish is essential.

Readings are taken at pre-established intervals (commonly, 0.004 or 0.005 in.), usually beginning at least 0. 001 in. from the edge of the workpiece.

Accuracy, Precision, and Bias. Many factors (Table 5) can influence the quality of microindentation test results. In the early days of low-load (<100 gf) hardness testing, it was quickly recognized that improper specimen preparation can influence hardness test results. Most texts state that improper preparation yields higher test results because the surface contains excessive preparation-induced deformation. While this is certainly true, improper preparation may also create excessive heat, which reduces the hardness and strength of many metals and alloys. Either problem may be encountered due to faulty preparation.

Table 5 Factors affecting precision and bias in microindentation hardness testing

Instrument factors
• Accuracy of the applied load • Inertia effects, speed of loading • Angle of indentation • Lateral movement of the indenter or specimen • Indentation time • Indenter shape deviations • Damage to the indenter • Insufficient spacing between indents or from edges
Measurement factors
• Calibration of the measurement system • Resolving power of the objective • Magnification • Operator bias in sizing • Inadequate image quality • Nonuniform illumination
Material factors

- Heterogeneity in composition or microstructure
- Crystallographic texture
- Qualify of the specimen preparation
- Low reflectivity or transparency

For many years, it was considered necessary to electrolytically polish specimens so that the preparation-induced damage could be removed, thus permitting bias-free low-load testing. However, the science behind mechanical specimen preparation, chiefly due to the work of L. Samuels, has led to development of excellent mechanical specimen preparation procedures, and electropolishing is no longer required.

In addition, several operational factors must be controlled for optimum test results. First, it is good practice to inspect the indenter periodically for damage, for example, cracking or chipping of the diamond. If you have metrology equipment, you can measure the face angles and the sharpness of the tip. Specifications for Vickers and Knoop indenter geometries are given in ASTM E 384.

A prime source of error is the alignment of the specimen surface relative to the indenter. The indenter itself must be properly aligned perpendicular (±1°) to the stage plate. Next, the specimen surface must be perpendicular to the indenter. Most testers provide holders that align the polished face perpendicular to the indenter (parallel to the stage). If a specimen is simply placed on the stage surface, its back surface must be parallel to its polished surface. Tilting the surface more than one degree from perpendicular results in nonsymmetrical impressions and can produce lateral movement between specimen and indenter. However, in most cases, intending procedures are not the major source of error.

It is important to regularly check the performance of the tester with a certified test block. The safest choice is a test block manufactured for microindentataion testing and certified for the test (Vickers or Knoop) as well as the specified load. Strictly speaking, a block certified for Vickers testing at 300 or 500 gf (commonly chosen loads) should yield essentially the same hardness with loads from about 50 to 1000 gf. That is, if you take the average of about five indents and compare the average at test load to the average at the calibrated load (knowing the standard deviation of the test results), statistical tests can tell (at any desired confidence level) if the difference between the mean values of the tests at the two loads is statistically significant or not.

When considering a new tester, it is prudent to perform a series of indents (five is adequate) at each test load (L) available. Then, plot the mean and 95% confidence limits of each test as a function of load. Because of the method of defining HV and HK, which involves dividing by d^2, measurement errors become more critical as d gets smaller; that is, as L decreases and the material's hardness increases. Therefore, departure from a constant hardness for the Vickers or Knoop tests as a function of load becomes a greater problem as the hardness increases. For the Knoop test, HK increases as L decreases because the indent geometry changes with indent depth and width. But the change in HK varies with the test load. At a higher test load the change is greater as L decreases.

The greatest source of error is measuring the indent. The indent should be placed in the center of the measuring field, because lens image quality is best in the center. The light source should provide adequate, even illumination to provide maximum contrast and resolution. The accuracy of the filar micrometer or other measuring device should be verified by a stage micrometer.

Specimen preparation quality becomes more important as the load decreases, and it must be at an acceptable level. Specimen thickness must be at least 2.5 times the Vickers diagonal length. Because the Knoop indent is shallower than the Vickers at the same load, somewhat thinner specimens can be tested. Spacing of indents is important because indenting produces plastic deformation and a strain field around the indent. If the spacing is too small, the new indent will be affected by the strain field around the last indent. ASTM recommends a minimum spacing (center to edge of adjacent indent) of 2.5 times the Vickers diagonal. For the Knoop test, in which the long diagonals are parallel, the spacing is 2.5 times the short diagonal. The minimum recommended spacing between the edge of the specimen and the center of the indent should be 2.5 times. Again, Knoop indents can be placed closer to the surface than Vickers indents.

Tension Testing

THE TENSION TEST is the test most commonly used to evaluate the mechanical properties of materials. Its chief use is the determination of properties related to the elastic design of machines and structures. In addition, the tension test gives information on a material's plasticity and fracture. The chief advantages of the tension test are the stress state is well established, the test has been carefully standardized, and the test is relatively easy and inexpensive to carry out. This article does not detail this test technique, because it is well covered by standard methods, such as ASTM specification E 8; instead, the interpretation and limitations of the test results are discussed.

Engineering Stress-Strain Curve

In the conventional engineering tension test, stress is defined by the applied load divided by the original cross-sectional area of the specimen. Engineering strain, *e*, is the change in length divided by the initial length:

$$e = \frac{L - L_0}{L_0} = \frac{\Delta L}{L_0} \qquad \textbf{(Eq 1)}$$

In the elastic region of the stress-strain curve (Fig. 14), stress is linearly related to strain, $\sigma = E \cdot e$, where E is the elastic modulus. As long as the specimen is loaded within the elastic region, the strain is totally recoverable and the specimen will return to its original length when the load is relaxed to zero. However, when the load exceeds a value corresponding to the yield stress, the specimen undergoes gross plastic deformation and is permanently deformed when the load returns to zero. The stress to produce continued plastic deformation increases with increasing strain--the metal strain hardens. To a good engineering approximation, the volume remains constant during plastic deformation, $AL = A_0L_0$, and, as the specimen elongates, it decreases uniformly in cross-sectional area along its gage length. Initially, the strain hardening more than compensates for this decrease in area, and the engineering stress continues to rise with increasing strain. Eventually a point is reached where the decrease in area is greater than the increase in deformation load arising from strain hardening. This condition will be reached first at some point in the specimen that is slightly weaker than the rest. All further plastic deformation is concentrated in this region, and the specimen begins to neck or thin down locally. Because the cross-sectional area is now decreasing far more rapidly than the deformation load is being increased by strain hardening, the engineering stress continues to decrease until fracture occurs.

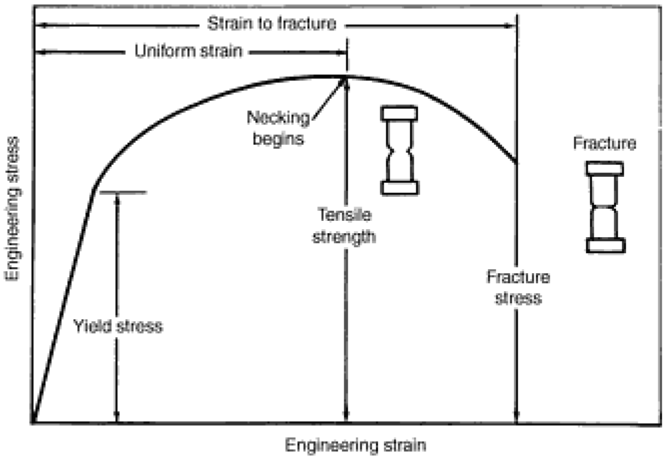


Fig. 14 Engineering stress-strain curve

The maximum in the engineering stress-strain curve corresponds to the ultimate tensile strength, σ_u. The strain at maximum load, up to which point the cross-sectional area decreases uniformly along the gage length as the specimen elongates, is the uniform elongation, e_u. For stretching-type forming operations, such as stretch forming of aircraft components or forming of automobile fenders, local necking determines the formability limit, and in such applications uniform elongation can be an important measure of ductility. In many metals, the engineering stress-strain curve is relatively flat in the vicinity of necking, and it may not be possible to establish the maximum load without ambiguity.

Ductility

The conventional measures of ductility that are obtained from the tension test are the engineering strain at fracture, e_f (usually expressed as a percentage elongation), and the reduction of area at fracture, RA (also usually expressed as a percentage):

$$e_f = \frac{L_f - L_0}{L_0} \tag{Eq 2}$$

$$RA = \frac{A_0 - A_f}{A_0} \tag{Eq 3}$$

Because an appreciable fraction of the deformation will be concentrated in the necked region of the specimen, the value of e_f will depend on the gage length L_0 over which the measurement was taken. The smaller the gage length, the greater the contribution from the neck, and the higher the value of e_f.

To eliminate this difficulty and to provide a measure of ductility that correlates with forming operations in which the gage length is very short, it is possible to determine the zero-gage-length elongation, e_0. From the constancy-of-volume relationship for plastic deformation, $AL = A_0L_0$:

$$\begin{aligned} \frac{L}{L_0} &= \frac{A_0}{A} = \frac{1}{1 - RA} \\ e_0 &= \frac{L - L_0}{L_0} = \frac{A_0}{A} - 1 \\ &= \frac{1}{1 - RA} - 1 = \frac{RA}{1 - RA} \end{aligned} \tag{Eq 4}$$

Thus, the zero-gage-length elongation may be determined directly from the reduction of area at fracture or from the change in length of grid marks near the actual fracture.

True-Stress/True-Strain Curve

The necking phenomenon that occurs in the tension test clouds the usefulness of the engineering stress-strain curve beyond the maximum load. The falloff in stress that occurs beyond P_{max} is artificial and occurs only because the stress continues to be calculated on the basis of the original cross-sectional area, A_0, when in fact the area at the necked region is now much smaller than A_0. If the true stress, based on the actual cross-sectional area of the specimen, is used, the stress-strain curve increases continuously up to fracture. Then, if strain is expressed as true strain, we have a plot called the true-stress/true-strain curve (Fig. 15).

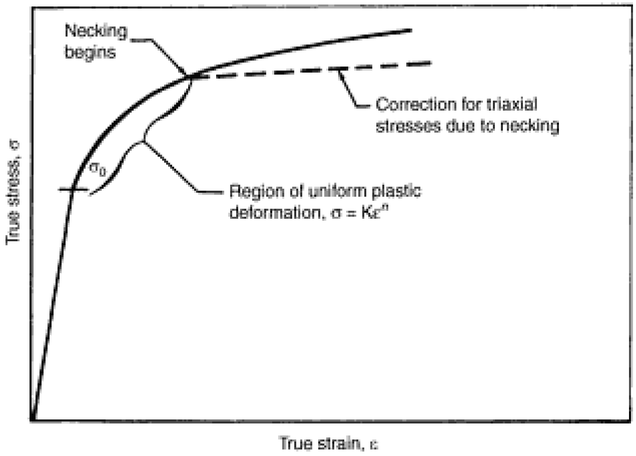


Fig. 15 True-stress/true-strain curve (flow curve)

Note that this curve continues to rise beyond necking all the way to fracture. However, once necking occurs, the constraints produced by the nonforming region outside the neck produce a state of triaxial stress in the neck. Thus, the average stress required to cause flow from maximum load to fracture is higher than would be required if only a uniaxial stress were present. Mathematical analysis of the stresses in the neck that permits correction of the true-stress/true-strain curve for the existence of triaxial stresses.

The region from yielding to necking is one of uniform plastic deformation in which the specimen gage length increases and the diameter decreases uniformly along the gage length. In this region the true-stress/true-strain curves for many ductile metals can be expressed by a power-law relation:

$$\sigma = K\varepsilon^n \qquad \textbf{(Eq 5)}$$

where K is the strength coefficient, defined by the value of true stress at $\varepsilon = 1.0$, and n is the strain-hardening exponent. Equation 5 is valid if a plot of σ versus ε is a straight line on log-log coordinates. The strain-hardening exponent is the slope of this line. Thus:

$$n = \frac{d(\log \sigma)}{d(\log \varepsilon)} = \frac{d(\ln \sigma)}{d(\ln \varepsilon)} = \frac{\varepsilon \, d\sigma}{\sigma \, d\varepsilon} \qquad \textbf{(Eq 6)}$$

The strain-hardening exponent may have values from $n = 0$ (a perfectly plastic solid) to $n = 1$ (an elastic solid). Values of n for most metals are between 0.05 and 0.50.

An increase in strain rate increases the stress to produce plastic deformation (the flow stress). The effect is modest for cold working but is quite significant for hot working. The dependence of flow stress on strain rate, at constant strain and temperature, is given by:

$$\sigma = C(\dot{\varepsilon})^m|_{\varepsilon, T} \qquad \textbf{(Eq 7)}$$

where m is the strain-rate sensitivity. The exponent m can be evaluated from the slope of a plot of log σ versus log $\dot{\varepsilon}$, or it can be obtained from rate-change tests in which the change in flow stress caused by a step change in $\dot{\varepsilon}$ is measured:

$$\begin{aligned} m &= \left(\frac{d \log \sigma}{d \log \dot{\varepsilon}}\right) \approx \left(\frac{\Delta \log \sigma}{\Delta \log \dot{\varepsilon}}\right)_{\varepsilon, T} \\ &= \frac{\log \sigma_2 - \log \sigma_1}{\log \dot{\varepsilon}_2 - \log \dot{\varepsilon}_1} = \frac{\log (\sigma_2/\sigma_1)}{\log (\dot{\varepsilon}_2/\dot{\varepsilon}_1)} \end{aligned} \qquad \textbf{(Eq 8)}$$

Analysis of Tensile Instability

The development of a necked region in a specimen loaded in uniaxial tension represents a plastic instability. Because this disturbs the simple analysis of the tension test and limits the engineering usefulness of the test, it has become the subject of considerable study. A practical application of the ideas presented is given in the work of Ghosh (*Met. Trans.*, Vol 8A, 1977, p 1221), who developed a numerical analysis for predicting the shape of the engineering strain-stress curve beyond maximum load as a function of strain hardening, strain-rate hardening, and plastic anisotropy properties of the metal.

Consider a tensile specimen loaded to a value P. At any point a distance L along the specimen, the cross-sectional area is A and $P = \sigma A$. Since P does not vary along the length of the specimen, and $\sigma = f(\varepsilon, \dot{\varepsilon})$:

$$\frac{dP}{dL} = 0 = A\left\{\left(\frac{d\sigma}{d\varepsilon}\right)_{\dot{\varepsilon}} \frac{d\varepsilon}{dL} + \left(\frac{d\sigma}{d\dot{\varepsilon}}\right)_{\varepsilon} \frac{d\dot{\varepsilon}}{dL}\right\} + \sigma \frac{dA}{dL} \qquad \textbf{(Eq 9)}$$

Because the volume of the specimen remains constant, the true strain can be written:

$$d\varepsilon = \frac{dL}{L} = -\frac{dA}{A} \qquad \textbf{(Eq 10)}$$

and

$$\frac{d\varepsilon}{dL} = -\frac{1}{A}\frac{dA}{dL} \qquad \textbf{(Eq 11)}$$

Also, from Eq 10, the strain-rate $\dot{\varepsilon}$ can be expressed:

$$d\dot{\varepsilon} = \frac{d\varepsilon}{dt} = -\frac{1}{A}\frac{dA}{dt} = -\frac{\dot{A}}{A} \qquad \textbf{(Eq 12)}$$

so that

$$\frac{d\dot{\varepsilon}}{dL} = -\frac{1}{A}\frac{d\dot{A}}{dL} + \frac{\dot{A}}{A^2}\frac{dA}{dL} \qquad \textbf{(Eq 13)}$$

The material parameters important to the necking process are the dimensionless work-hardening coefficient:

$$\gamma = \frac{1}{\sigma}\frac{d\sigma}{d\varepsilon} \qquad \textbf{(Eq 14)}$$

and the strain-rate sensitivity:

$$m = \left(\frac{d\ln\sigma}{d\ln\dot{\varepsilon}}\right)_{\varepsilon} = \frac{\dot{\varepsilon}}{\sigma}\left(\frac{d\sigma}{d\dot{\varepsilon}}\right)_{\varepsilon} \qquad \textbf{(Eq 15)}$$

When Eq 12 and 13 are substituted into Eq 9, and the definitions for γ and *m* are added through Eq 14 and 15, the result is:

$$\frac{dA}{dL}(\sigma - m\sigma - \gamma\sigma) = \frac{d\dot{A}}{dL}\frac{m\sigma A}{\dot{A}} \qquad \textbf{(Eq 16)}$$

A final rearrangement gives

$$\frac{(1/\dot{A})\,(d\dot{A}/dL)}{(1/A)\,(dA/dL)} = \frac{(d/dL)\,(\ln \dot{A})}{(d/dL)\,(\ln A)} = \frac{m + \gamma - 1}{m} \qquad \textbf{(Eq 17)}$$

This equation describes the rate of change of area with length, and gives the criterion for the onset of necking.

Any real tension specimen will have variations in cross-sectional area along its length. These can arise from an intentional taper, from machining errors, or from heterogeneities of structure that lead to weaker cross sections. Deformation becomes unstable when the smallest cross section of the specimen shrinks faster than the rest. This occurs when $d\dot{A}/dA > 0$. Deformation will be uniform and stable when $d\dot{A}/dA < 0$. Because $\dot{A}/A$ is negative in tension, stable deformation in tension occurs when $d\dot{A}/dA \geq 0$. Therefore, from Eq 17, the condition for stable, uniform tensile deformation is:

$$\gamma + m \geq 1 \qquad \textbf{(Eq 18)}$$

Necking is involved with the interplay between the applied stress and the flow resistance of the material. As the specimen elongates under a given load the area decreases and the stress increases. If necking is not to occur, the material's strength must increase through strain hardening (γ) and strain-rate hardening (m).

For room-temperature deformation, $m \to 0$ and the instability criterion reduces to $\gamma \geq 1$. Thus, stable tensile deformation occurs for

$$d\sigma/d\varepsilon \geq \sigma \qquad \textbf{(Eq 19)}$$

If the true-stress/true-strain curve is given by $\sigma = K\varepsilon^{a}$, then

$$d\sigma/d\varepsilon = nK\varepsilon^{n-1} = \sigma = K\varepsilon^{n}$$

and necking occurs when

$$\varepsilon = n \qquad \textbf{(Eq 20)}$$

Because n in tension rarely exceeds 0.5, the available uniform strain in the tension test is limited.

Elongation Measurements in Tension Testing

The measured elongation depends on the gage length or the dimensions of the cross section of the specimen. This is because the total extension consists of two components, the uniform extension up to the point of necking and the localized extension after necking (Fig. 16). The extent of uniform extension will depend on the metallurgical condition of the material (through n) and the effect of specimen size and shape on the development of a neck.

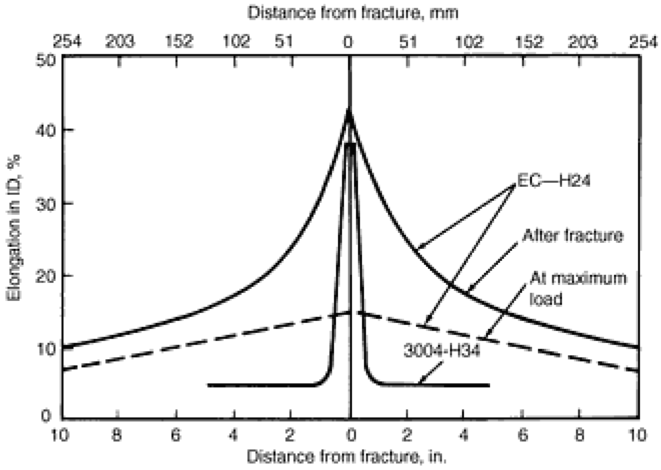


Fig. 16 Local elongation measured at positions away from fracture in tension specimens for two aluminum alloys

However,

$$L_f - L_0 = a + e_u L_0 \qquad \textbf{(Eq 21)}$$

where a is the local necking extension and $e_u L_0$ is the uniform extension. We then have

$$e_f = \frac{L_f - L_0}{L_0} = \frac{a}{L_0} + e_u \qquad \textbf{(Eq 22)}$$

which clearly indicates that the total elongation is a function of the gage length. Numerous attempts to rationalize the strain distribution in the tension test have been made, dating back to 1850. Following Barba's law, which states that geometrically similar specimens develop geometrically similar necks, it is usually assumed that the local extension at the neck is proportional to the linear dimension of the cross-sectional area, $a = \beta\sqrt{A_0}$, so that the elongation equation becomes:

$$e_f = \frac{\beta\sqrt{A_0}}{L_0} + e_u \qquad \textbf{(Eq 23)}$$

This equation for elongation clearly shows the rationale for the use of fixed ratios of gage length to diameter or gage length to square root of cross-sectional area in specifying tensile-specimen dimensions. It also reinforces the importance of stating the gage length over which the measurement was made when reporting elongation values. In the United States, the standard tensile specimen is 0.505 in. (12.83 mm) in diameter and 2 in. (50.8 mm) in gage length, so $1/D \approx 4$. However, the testing standards in other countries specify different gage lengths for the measurement of elongation (Table 6).

Table 6 Dimensional relationships for specimens used in different countries for measurement of elongation

Type of specimen	Dimensional relationship	United Kingdom		United States (ASTM)	Germany
		Before 1962	**Current**		
Sheet	$L_0/\sqrt{A_0}$	4.0	5.65	4.5	11.3
Round bar	L_0/D_0	3.54	5.0	4.0	10.0

To compare the ductilities of different metals by elongation measurements, the gage length should be adjusted as a function of the cross-sectional area of the test specimen. However, when flat specimens are cut from sheet or plate primarily to determine whether quality of individual lots meets specifications, it is usual to use fixed gage lengths, because of the lower cost of preparing and testing a large number of such specimens.

The effect of specimen geometry on total elongation is of particular concern in testing of sheet-metal specimens. Although the Unwin equation (Eq 23) may be obeyed (within considerable scatter), a simpler equation due to Templin is possibly in better agreement with the results:

$$e_{\mathrm{f}} = \mathrm{C}(A)^{b} \qquad \textbf{(Eq 24)}$$

Analysis of the results showed that the exponent b in Templin's equation depends on both uniform strain and localized fracture strain. Thus it will vary with processing and heat-to-heat differences in the metal, and it cannot be considered to be a real constant of the metal. A general trend was shown to exist between the exponent b in Templin's equation and the logarithm of the ratio of the zero-gage-length (fracture-strain) elongations to the infinite-gage-length (uniform-strain) elongations.

Although (even after 100 years of study) opinions differ in detail concerning the effect of specimen geometry on elongation, there is general agreement concerning the validity and importance of one factor--the ratio $\sqrt{A/L}$. Even here it appears to be better validated for round bars than for rectangular specimens. However, if sufficient data on the influence of specimen size on elongation are not available, the elongation of a specimen of arbitrary size can be estimated by using the concept that a constant elongation is obtained if $\sqrt{A/L}$is maintained constant, as suggested by Eq 23. Then, at a constant value of elongation, $\sqrt{A_1/L_1}+ \sqrt{A_2/L_2}$, where A and L are the areas and gage lengths of two different specimens, 1 and 2, of the same metal. To predict the elongation in length L_2 on a specimen with area A_2 from measurements on a specimen with area A_1, it is only necessary to adjust the gage length of specimen 1 to conform to $L_1 = L_2 \sqrt{A_1/L_1}$. As an example, suppose that sheet $\frac{1}{8}$in. (3.2 mm) thick is available, and it is desired to predict the elongation in 2 in. (50.8 mm) in identical material 0.080 in. (2.03 mm) thick. Using sheet specimens $\frac{1}{2}$in. (12.7 mm) wide, it is predictable that a test specimen with $L = 2 \sqrt{0.125/0.080} = 2.5$ in. (63.5 mm) from the $\frac{1}{8}$in. (3.2 mm) sheet would give the same elongation as a 2 in. (50.8 mm) gage length in sheet 0.080 in. (2.0 mm) thick. The usefulness of this procedure is shown in Fig. 17, where solid lines are experimental and points indicate predicted elongations for specimens of different areas.

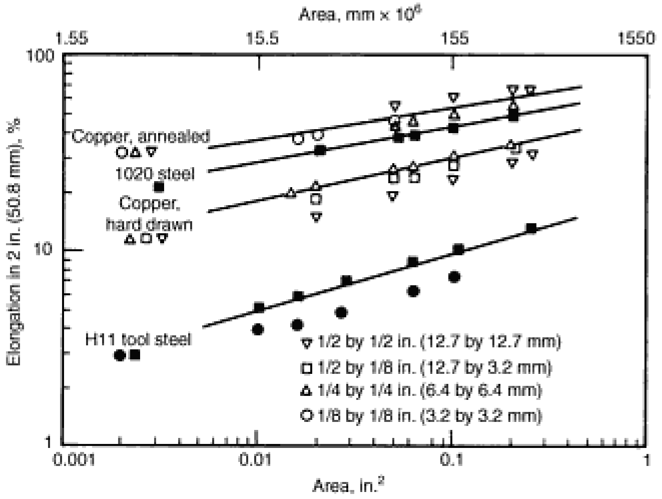


Fig. 17 Calculated variation of elongation in 2 in. (50.8 mm) with specimen cross-sectional area. Source: E.G. Kula and N.N. Fahey, *Mat. Res. Std.,* Vol 1, 1961, p 631

This discussion indicates that the measures of ductility available with the tension test leave a great deal to be desired in providing quantitative values. The main difficulty arises from the necking of the specimen. The occurrence of uniform and localized deformation makes the percentage elongation at fracture of little value as a quantitative measure of ductility, although it is usually required in metallurgical specifications. Reduction of area is a better measure of ductility, but its quantitative use is made difficult by the poorly defined triaxial stress state introduced by the formation of a neck.

Plane-Strain Tension Test

A special type of tension-test specimen has been designed to give maximum plastic constraint so as to emphasize the differences in fracture behavior of nominally ductile materials (Fig. 18). The deep grooves in the specimen restrict the deformation to the grooved region. The ratio B/L is large enough so that approximately plane-strain conditions are achieved in the test section. Thus, strain occurs in the thickness and length directions but not in the width direction. The true strain is given:

$$\varepsilon = \ln h_0/h \qquad \textbf{(Eq 25)}$$

where h_0 is the initial thickness of the reduced section and h is the thickness at any time after deformation has begun. However, the ratio L/h is large enough so that there is no notch effect, and thus a specimen designed to the specification in Fig. 18 is an unnotched plane-strain specimen. Thus, the true stress can be determine from the load divided by the area ($h \times B$).

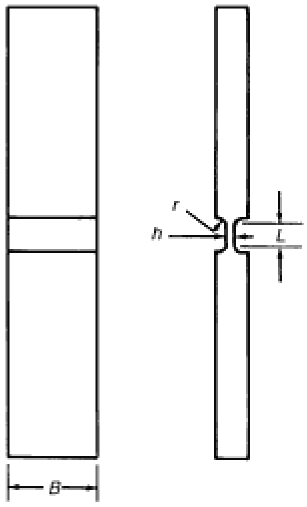


Fig. 18 Plane-strain tension specimen where B = 1 in.; L = $\frac{1}{4}$ in.; h = 0.080 in.; r = $\frac{1}{16}$ in.

The plane-strain tension specimen described in Fig. 18 has the disadvantage that it may not be practical to machine such a specimen in a thin sheet. Also, because deformation is confined to the notch region, it may be difficult to make axial-strain measurements in those limited confines. A special clip-on fixture allows a regular sheet specimen to be converted to a plane-strain specimen.

This plane-strain tension specimen is 38 mm wide and 200 mm long. The specimen contains two circular edge notches with a 19 mm radius. A special fixture containing four knife edges is clamped to the surface of the specimen. The knife edges run parallel to the tensile axis of the specimen and fall just inside the reduced cross section. These knife edges prevent any deformation in the width direction. As a result, necking and failure occur perpendicular to the tensile axis.

Summary

The tension test is a "benchmark test" or "reference test" that provides much basic information about the mechanical state of a material. This test provides information on the flow of a material and its ductility.

The flow resistance is evaluated on the basis of yield stress. The yield stress is variously determined by the first deviation from linear elastic behavior, or more precisely by the stress corresponding to the intersection with the stress-strain curve at an offset strain of 0.002 (the 0.2% offset yield strength). If the stress-strain curve can be expressed by Eq 5, then the yield stress corresponding to a particular cold reduction, expressed as reduction of area, RA, is given by the following equation:

$$\sigma_y = K \ln\left(\frac{1}{1 - RA}\right)^n \quad \textbf{(Eq 26)}$$

This shows that a high strain-hardening exponent *n* leads to higher flow stress. In addition, with high *n* values, the deformation is spread out and local points of weakness, which can lead to thinning or fracture, are minimized. At elevated temperatures, strain-rate sensitivity becomes important, and strain hardening becomes less important.

Elongation and reduction of area in the tension test cannot be calculated from each other because the occurrence of necking prevents the constant-volume relationship ($A_0L_0 = A_1L_1$) from being invoked over a distance containing the necked region. While elongation and reduction of area usually vary in the same way--for example, as a function of test temperature or alloy content--this is not always the case. Generally speaking, elongation and reduction of area measure different types of material behavior. Elongation measurements in the tension test are chiefly influenced by uniform elongation (except when the gage length is very short) and thus depend on the strain-hardening capacity of the material. Reduction of area is more a measure of the deformation required to produce fracture. It is the most structure-sensitive ductility parameter.

Compression Testing

THE CONCEPTS of uniaxial tensile and compressive loading are quite similar. In both cases, a strain is produced parallel to the applied load that has the same sign as the applied load, and two-transverse strains are produced that are opposite in sign to the applied load. Below the proportional limit, the strain in the load direction, in both cases, can be calculated using a single value of Young's modulus. Similarly, the transverse strain can be calculated using a second material constant, Poisson's ratio (ν):

$$\varepsilon_{\text{transverse}} = \nu\varepsilon_{\text{axial}}$$

Compression testing is an extremely valuable testing procedure, which is often overlooked because it is not properly understood. One of the main advantages of the compression test is that tests can be performed with a minimum of material, and thus mechanical properties can be obtained from specimens that are too small for tension testing. Compression tests are also very helpful for predicting the bulk formability of materials (behavior in forging, extrusion, rolling, etc.).

In compression testing, the material does not neck as in tension, but undergoes barreling; failure occurs by different mechanisms and therefore there is no ultimate tensile strength (UTS). In general, ductile materials do not fail in compression but tend to flow in response to the imposed loads. Brittle cylindrical specimens loaded in compression fail in shear on a plane inclined to the load, and therefore actually break into two or more pieces. In this case, an ultimate (compressive) stress can be defined.

In comparison with tension testing, several difficulties are encountered in conducting compression tests and interpretation of the experimental data. For example, maintaining complete axiality of the applied load is important. In tension testing, self-aligning grips make this relatively simple to accomplish. In compression testing, if the specimen is tall in relation to its diameter, this can present a major difficulty. Nonaxiality of the load induces a bending load in the specimen, in addition to the axial load, that potentially will cause buckling. Alignment of the loading platens to impose strict uniaxial loading is easier if the specimen contact area is large, but this in turn introduces other difficulties.

Frictional forces exist at the specimen/platen interface that tend to restrict the increase in diameter of the specimen as it decreases in height. These forces are directly related to the coefficient of friction, μ, and thus care must be given to minimizing μ. P is the compressive load. Due to these frictional forces, loading on the specimen is not uniaxial. The effect of these frictional forces is two fold; an analysis indicates that the magnitude of the applied stress is increased over what it would be if the specimen were loaded uniaxially (i.e., the situation if μequals 0), and diametral expansion is hindered near the platens, but not in material well removed from the platen, so that the specimen becomes barrel shaped (Fig. 19). Because of the increased magnitude of the applied stress, deformation at midheight is plastic, whereas it is still elastic near the specimen/platen interface. The ratio of the elastically strained material to the plastically strained material increases as the specimen height decreases, so that barreling increases during the course of a test. The unfortunate consequence of barreling is that specimens selected for easy axial alignment are the same specimens that show extensive barreling and for which the internal stresses in the material have a large biaxial component. Therefore, some compromise must be made in selecting specimen dimensions. A height-to-diameter ratio of about 3 to 1 often is selected to minimize buckling that occurs due to bending loads generated by nonaxial alignment of the load.

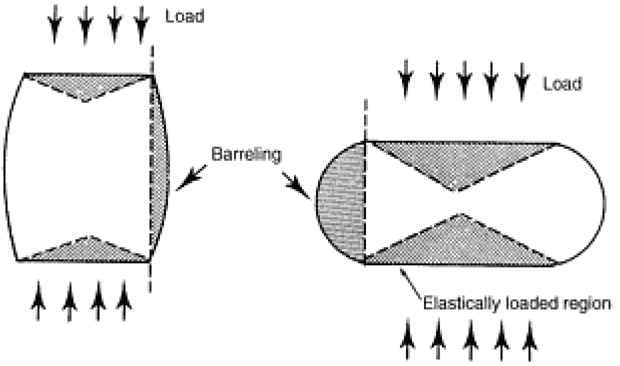


Fig. 19 Elastically loaded region and barreling in a compression specimen for two different height-to-width ratios

Because of the increasing contact area and the elastically strained material near the platen, the load-deflection curve bends upward as the specimen decreases in height (Fig. 20). A dramatic increase in load occurs if the elastically strained regions of Fig. 19 overlap.

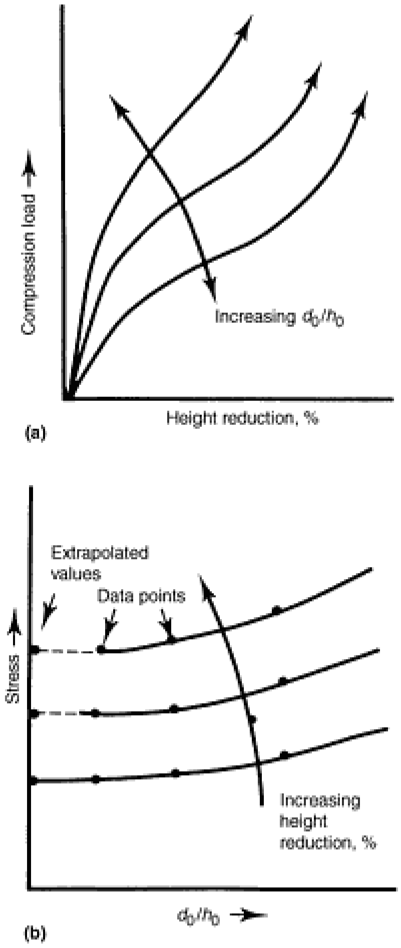


Fig. 20 Load-deflection curves. (a) Curves illustrating the relationship of compression load to height reduction for various d_0/h_0 ratios. (b) Replot of curves for extrapolation to $d_0/h_0=0$. d_0 is initial diameter; h_0 is initial height.

Due to the presence of frictional forces, the pressure distribution across the specimen is not uniform, as shown in Fig. 21. The pressure distribution is given:

$$p = \sigma_0 \exp[(2\mu/h)(r-x)]$$

where p is pressure, σ_0 is yield stress, μ is coefficient of friction, r is cylinder radius, x is distance from center of cylinder to data point on x-axis, and h is cylinder height.

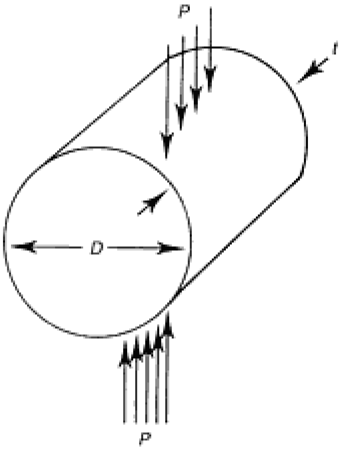


Fig. 21 Line-loaded compression disk

Figure 20 also shows how the pressure distribution changes as the height decreases and as the coefficient of friction changes. The load needed to deform the cylinder can be estimated by multiplying the average pressure on the specimen by the contact area. Figure 20 indicates that the load required to deform materials increases dramatically as the diameter-to-height ratio becomes greater and also increases with rise in the coefficient of friction. Without overload protection on the load cell, precautions must be taken so that the large loads required to cause plastic flow do not damage the load cell by exceeding its capacity, especially at the large plastic strains characteristics of forming processes.

Coefficients of friction are kept as low as possible to minimize barreling and the development of large loads by providing lubrication at the platen/specimen interface. Two possibilities are the use of lubricating oil and oil grooves in the specimen or platen, or thin Teflon (E.I. DuPont de Nemours & Co., Inc., Wilmington, DE) sheet between the platen and the specimen.

An alternative procedure to minimize friction effects and the attendant barreling phenomenon is the sequential loading of the specimen; that is, to load until plastic deformation just starts, unload, determine the change in dimensions and relubricate, then reload again until plastic flow initiates. This locus of points is then connected to provide a constructed stress-strain curve (Fig. 20).

A tedious but accurate way to determine a true uniaxial compression stress-strain curve is to use a series of specimens having varying l/D ratios. The stress at a given height reduction is then determined for each l/D ratio, plotted as a function of l/D ratio, and extrapolated to an l/D ratio of 0. This might be done at only one value of offset (i.e., corresponding to 0.2% strain) to provide a true flow stress, or a complete curve could be constructed.

Line-Loaded Compression Testing

For the line-loaded test, a flat disk is loaded (Fig. 21). If the disk is of brittle material so that fracture occurs before plastic flow initiates, the thickness of the disk does not affect the calculated stress to cause fracture. The tensile stress at fracture for this case is calculated:

$$s = 2P/\pi Dt$$

where *s* is maximum tensile stress, *P* is applied load, D is specimen diameter, and *t* is specimen thickness. This test is known as the "Brazilian test" and is routinely applied to determine the tensile strength of rocks.

Plain-Strain Compression Testing

The common forming operations--rolling, swaging, and forging--are forming operations in which there is little or no change in dimension in one direction. For example, in rolling, a decrease in thickness is converted into an increase in length with little increase in width. Such a state of strain is then two dimensional; it is planar strain. Plane-strain deformation is referred to when the development of a local neck is discussed; and in that case, the plane-strain deformation occurred due to an internal state of strain in the body. Two loading situations that develop plane-strain deformation are illustrated here; one in which the plane-strain deformation is developed due to external constraint on the flowing material, and a second, in which the constraint is developed internally in the material.

In Fig. 22(a), metal can flow in the *x* and *z* directions due to the applied stress in the *z* direction, but cannot flow in the *y* direction because of the die wall. In Fig. 22(b), the load *P* causes flow in the *z* and *y* directions, but flow occurs in the *x* direction if the *x* dimension or the width-to-thickness ratio of the sheet is large. This is because the material not under the die has no load imposed on it and, therefore, has no tendency to spread in either the *x* or *y* direction. Therefore, this unloaded material restrains flow of the material in the *x* direction (but not the *y* direction) under the die. There is net flow, in the *y* direction, because the unloaded material is simply pushed out by the expanding material under the die. Plane-strain conditions are realized when the width-to-thickness ratio is about 10 to 1. Because of frictional forces under the die, the *b*/*t* ratio should be held to between 2 to 1 and 4 to 1. If large decreases in thickness are obtained in the test, sequential loading with a change in die dimension is necessary to maintain this ratio. In any event, it is again possible to construct a stress-strain curve.

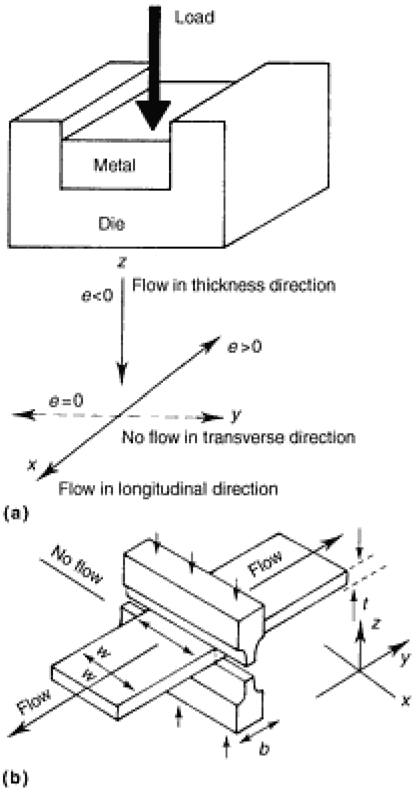

Load
Metal
Die
z
e<0
Flow in thickness direction
e>0
e=0
y
No flow in transverse direction
x
Flow in longitudinal direction
(a)
No flow
Flow
t
z
y
x
w
w
Flow
b
(b)

Fig. 22 Plane-strain compression. (a) Plane-strain compression of a block in a die. (b) Indenting dies for plane-strain compression testing. Source: R.N. Parkins, *Mechanical Treatment of Metals,* Elsevier, 1968, p 22

Because the strains are large, true stresses and strains frequently are calculated rather than the nominal stresses and strains. The stress and strain developed in the plane-strain compression test are then given:

$$\sigma_T = \frac{\text{load}}{\text{area}} = \frac{P}{(w)(b)}$$

and

$$\varepsilon T = \ln (t/t_0)$$

Although not derived here, the mean stresses and the strain in the load direction in plane-strain deformation are related to the stress and strain developed in a uniaxial compression test of a cylinder:

$$\sigma_{\text{plane strain}} = 1.15\sigma_{\text{uniaxial compression}}$$

and

$$\varepsilon_{\text{plane strain}} = 1.15\varepsilon_{\text{uniaxial compression}}$$

Therefore, stresses and strains measured in the plane-strain compression test must be divided by the factor 1.15 if an equivalent curve for uniaxially loaded material is to be constructed or if the data are to be compared with data obtained in a uniaxial test.

Upset Testing

Bulk forming processes, such as forging, extrusion, and rolling, are also evaluated for formability by upset testing. In the simplest form of this test, a short cylinder is flattened (upset) into a pancake shape. The bulging at the edges produces tensile stresses that cause fractures. Workability is evaluated by determining the largest deformation that can be achieved without producing edge cracking. More typical, however, is use of the hot upset test over a range of temperatures to establish the working temperature that minimizes fracture.

A precision upset test has been developed to determine the three-dimensional analog of the forming-limit diagram. If grid lines are electroetched on the surfaces of small cylinders, then the compressive axial strain (ε_z) and the tensile hoop strain ($\varepsilon\theta$) at which fracture occurs can be determined. By varying the length-to-diameter ratios (l/D) of the cylinders and the lubrication at the cylinder ends, a wide range of stress states can be developed. By observing the strain in the upset cylinder at which surface fracture just occurs for each of the stress states, a fracture-locus line can be established (Fig. 23). For any combination of strains below the fracture-locus line, fracture has not yet occurred and the condition is safe. When the strain path crosses the fracture line, surface fracture has occurred. This procedure is helpful in predicting the bulk formability of metals.

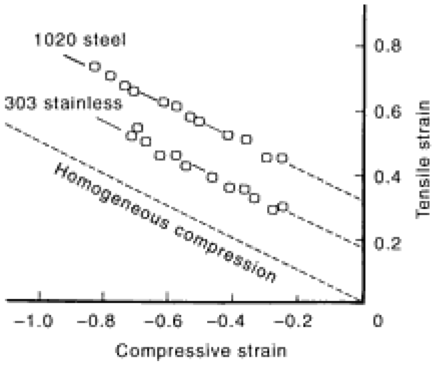


Fig. 23 Fracture-locus lines

Dynamic Fracture Testing

THE MOST IMPORTANT fracture tests can be grouped into two categories: impact (dynamic-fracture) tests and fracture-toughness tests. However, the variety of service circumstances--different types of materials, differing crack morphologies, differing environments and loading rates, effects of size--have spawned a large number of fracture tests, some highly specialized.

The most common impact tests are the Charpy test and the Izod test. Both are used primarily for low- and medium-strength materials (typically steels). These materials may break at stresses either above or below yield, depending on the circumstances (temperature, size of crack, etc.). Fracture-toughness tests are intended primarily for medium- and high-strength materials that may break at below-yield stresses, if a crack or other sharp flaw--often quite small--is present. Fracture-toughness tests are based on the theoretical developments of fracture mechanics and give results that can be directly used in calculations relating the size of cracks to applied loads and stresses. In fracture-toughness tests, unlike in impact tests, loads are normally applied relatively slowly--at about the same rate as in an ordinary tension test--and temperature need not be of concern. Although fracture-toughness tests can be conducted in a tension-test machine, the specimen looks quite different. Generally, it is a plate containing a crack grown from a machined notch, rather than the smooth round bar used in tension testing.

Impact tests feature a high but generally indeterminate rate of loading, typically generated by a swinging pendulum or falling weight. The results are not directly related to the stresses and deformations normally calculated during the course of engineering analysis and design, although the results may relate to the temperatures experienced in service. In general, impact-test results have significance based on empirical correlations with service experience, or as a means of comparing materials. The Charpy test is most commonly used to evaluate the effects of metallurgical processes on dynamic mechanical properties. Another test, the Izod impact test, employs a cantilevered specimen hit by a swinging pendulum.

Charpy Tests

Specimens used for Charpy tests come in several different configurations. Two examples are the V-notch test specimen, containing a shallow 45° machined notch as a stress concentrator, and the Charpy keyhole specimen, with a stress raiser that looks something like a keyhole (Fig. 24a and b). The V-notch test is the more common of the two tests.

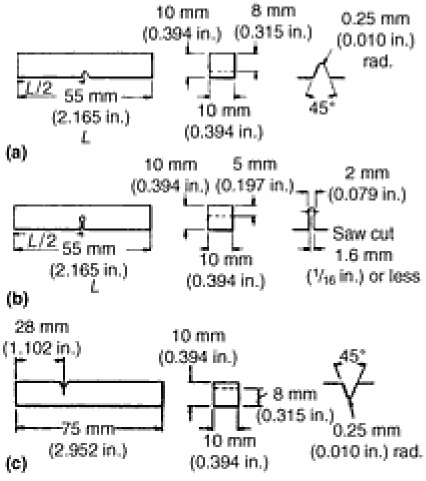


Fig. 24 Notched-bar impact-test specimens. (a) Simple beam V-notch Charpy specimen. (b) Simple beam keyhole-notch Charpy specimen. (c) Cantilever beam notched Izod specimen. Source: Notched Bar Impact Testing of Metallic Materials, E 23-81, ASTM, 1981

Charpy tests have the virtue of being simple and inexpensive. Furthermore, the specimen is small--also one of the limitations of the test--and Charpy testing machines are widely available. The principal application is for delineating the transition-temperature region in low- and medium-strength steels; in the common test sequence, a series of nominally identical specimens is broken at different temperatures. (Occasionally this test is used for materials other than low- and medium-strength steel.) Material specifications often include required levels of Charpy test performance, but the results of the test have limited fundamental significance. Results only have meaning in terms of correlations with ductile or brittle behavior under service conditions based on actual experience. However, because Charpy tests have been employed for so many years, a good deal of this experience is available in the form of general rules that can be exploited by designers.

Figure 25 illustrates the Charpy bar supported at its ends and struck on the surface opposite the notch so that the loading is three-point bending. The source of the blow is a heavy, swinging pendulum with a range of 35 to 325 J (25 to 240 ft · lb) of energy at impact. The weight and height of the pendulum striking head may be modified to produce various joules (foot-pounds) of energy. Testing-machine and specimen details for Charpy tests, together with test procedures, are standardized, as described in ASTM E 23.

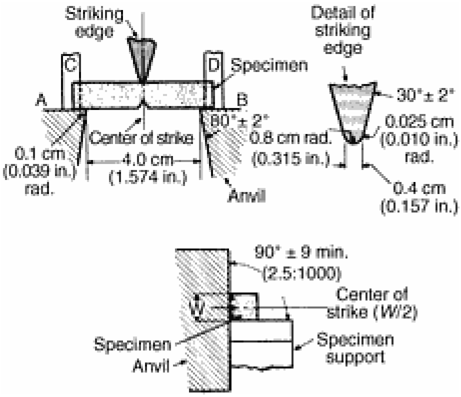


Fig. 25 Setup and specimen for Charpy impact testing

Machining of specimens should be controlled to provide specimen uniformity. The orientation of the bars, with respect to the rolling direction, often has considerable effect on impact behavior.

In its simplest form, a Charpy test is conducted by inserting a specimen into the machine, cocking the pendulum, and releasing it to fracture the test bar. Typically, a series of tests is performed at different temperatures. Charpy machines should be periodically checked against standardized specimens to determine their accuracy.

In addition to data on energy absorbed, two other quantities are commonly determined for each impact-test specimen. First, the percentage of fibrous fracture area visible on the cross section of the broken specimen is compared with the percentage of cleavage area. Second, the lateral contraction of the broken bar at the root of the notch is measured.

Figure 26 shows a series of fracture surfaces from Charpy V-notch tests at different temperatures. The fracture surface is entirely fibrous in appearance above the transition-temperature region, indicating ductile behavior; it is entirely cleavage below. In the transition region, small decreases in temperature increase the percentage of cleavage fracture. As Fig. 26 shows, the texture difference between fibrous and cleavage regions makes identification straightforward for specimens (such as annealed low-carbon steel), which fail by cleavage at low temperatures. The percentages can be estimated visually or, if more precision is needed, the fracture surfaces can be photographed and further analyzed. Note that in the transition region, cleavage takes place in the center of the specimen, with fibrous fracture near the outer surfaces of the bar. This is a result of the differing states of stress in the interior and near the surface. The inner material is constrained against plastic deformation and more likely to fracture by cleavage.

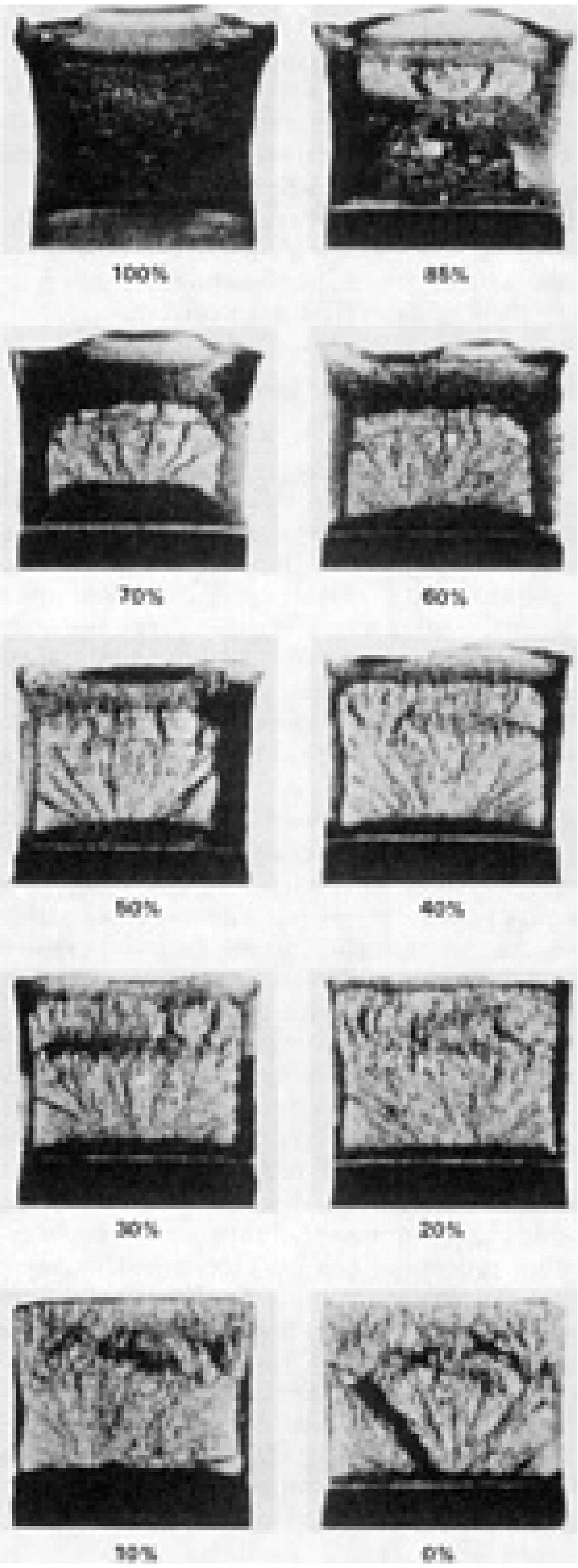


Fig. 26 Series of fractographs of Charpy V-notch specimens of 4340 steel tested at different temperatures, showing the change in appearance and estimated percentages of fibrous fracture. Source: Army Materials and Mechanics Research Center, Watertown Arsenal

Notch-root contraction is also a direct indication of fracture behavior--in this case, of the amount of plastic deformation accompanying the fracture. The contraction is usually easiest to measure with a micrometer caliper. The thickness of the unbroken specimen at the notch root should be measured before the test.

The energy absorbed and the fracture-surface appearance are the most commonly specified results of the Charpy test. For example, steels for certain applications may be required to have a certain minimum level of energy absorption--15 or 20 J (10 or 15 ft · lb) are common values--at the lowest expected service temperature. Alternately, some minimum percentage of fibrous fracture (e.g., 50%) may be required. Again, note that such requirements have no intrinsic significance and can only be defined based on correlations with service experience.

The energy absorbed in impact, percentage of fibrous fracture, and notch-root contraction can be plotted against temperature to determine the ductile-to-brittle transition temperature. However, the particular definition of the ductile-to-brittle transition temperature must be clearly specified in the data report.

The standard Charpy impact test yields direct readings only of the energy absorbed. "Instrumented" tests make use of testing machines with auxiliary sensors to acquire other data, typically load data. A specially made striking tup instrumented with strain gages can give a load-time history that allows initiation of the crack from the machined notch to be distinguished from propagation of that crack through the specimen. This is a relatively specialized test utilized for specific limited applications. The advantages of the basic Charpy test, small specimen size, and low cost, are retained, while allowing fracture-mechanics parameters, such as toughness, to be estimated under specific circumstances.

The Izod Test

The Izod test is a cantilever-beam test as compared to the simple-beam Charpy test. As shown in Fig. 27, the Izod specimen is held in a fixture wit, the V-notch facing the striking anvil of the pendulum. The center of the V-notch is in the same plane as, and parallel to, the supporting fixture. The actual fracture test is performed in the same manner as the Charpy test, and data on energy consumed are reported in joules (foot-pounds). The Izod test does not lend itself to variable-temperature testing because of the appreciable time required to place and clamp the specimen, which results in rapid temperature change due to specimen and fixture contact. Izod tests are generally specified for materials tested at room temperature and where the engineering part is designed to operate under cantilever loading.

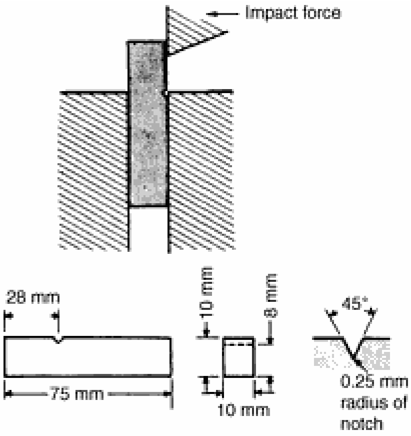


Fig. 27 Setup and specimen for Izod impact testing

Dynamic Tear Tests

Dynamic tear tests and drop-weight tear tests come in several varieties, two of which have been standardized by ASTM. All are similar to the Charpy test in the use of the kinetic energy of a swinging pendulum (or occasionally a failing weight) to break an artificially notched test specimen. In essence, they are larger versions of the Charpy test, with test specimens that are both thicker and wider to represent the fracture behavior of thick-section structural materials. While the Charpy test is used almost exclusively to investigate the transition-temperature behavior of low- and medium-strength steels, dynamic tear (DT) tests can be used as well for high-strength steels and for aluminum and titanium alloys. When such materials are broken in a Charpy machine, the energy absorbed is typically so low, compared to the testing machine's capacity, that little meaningful information can be obtained. The larger DT specimen allows different alloys and heat treatments to be more reliably compared.

Typical DT specimens are shown in Fig. 28. The larger specimen is used only where full-thickness tests representative of actual structures must be undertaken.

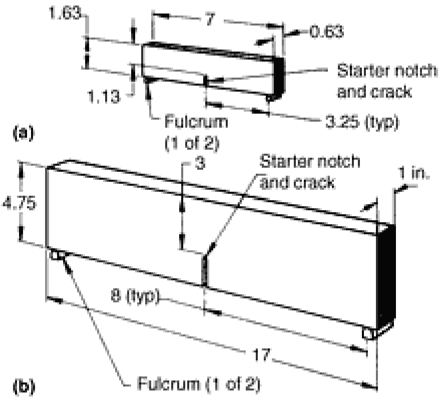


Fig. 28 Two sizes of the standard specimen for the Naval Research Laboratory standardized dynamic tear test. In the specimens, a crack with a sharp tip is produced by making a brittle electron beam weld or by pressing with a knife edge. With either method of providing the crack tip, and with either size of specimen, maximum-constant conditions are attained. Dimensions are in inches.

As in a Charpy test, the basic information obtained from a DT test is the energy absorbed in breaking the specimen, although fracture-surface appearance and the extent of plastic deformation near the fracture can also be useful.

The two varieties of ASTM standard dynamic tear or drop-weight tests have the designations E 436 ("Drop-Weight Tear Tests for Ferritic Steels") and E 604 ("Dynamic Tear Testing of Metallic Materials"). As the names imply, the purposes are quite different, even though the general features are similar.

The E 436 drop-weight tear test uses a specimen, normally of the actual thickness of the steel plate being investigated, with an easily produced, pressed notch (see ASTM E 436 for details). The test is used only for steel and indicates the transition temperature between ductile and brittle behavior. To this end, specimens are tested at increasing (or decreasing) temperatures until the crack propagates as a fully developed fibrous fracture away from the notch (it makes no difference if the crack initiates by a cleavage mechanism). This is determined by visual examination of the fractured specimen; no quantitative data need be gathered. Thus, the test is simple and inexpensive. It is used primarily for quality control purposes on structural steels, notably for pipeline applications.

The ASTM E 604 test differs in two fundamental ways: the energy absorbed in fracturing the specimen is measured, and the test can be used on materials other than steels.

The standard dimensions of the specimen are less than for either of the specimens shown in Fig. 28; the notch is machined, and the specimen is always 15.9 mm ($\frac{5}{8}$ in.) thick. Tests can be conducted at a fixed temperature to compare several materials; or over a range of temperatures to investigate transition-temperature effects. Considerable effort has gone into correlating DT test results with plane-strain fracture-toughness values, because the more sophisticated testing procedures required for the latter are more costly and time consuming. In some cases, the DT test can be used to estimate plane-strain toughness.

Drop Weight Test

As the name implies, in a drop weight test (DWT) the specimen is broken by a falling weight rather than by a pendulum. However, the essential difference between this test and those described earlier is that it provides the operational definition of an important parameter termed the nil-ductility temperature (NDT). The NDT is the highest temperature at which a particular steel is likely to fracture in brittle fashion by cleavage. Above this temperature, the fracture will be accompanied by some macroscopic plastic flow associated with fibrous fracture and a microvoid-coalescence process on the microscale. The DWT procedure does not, however, require interpretation of the fracture appearance, nor must any quantitative data be gathered beyond the temperature of the specimen. As the definition of the term NDT implies, the test is used only for low- and medium-strength steels that show a cleavage-fibrous transition as the temperature is increased.

The DWT also has been standardized by ASTM (E 208). The specimen is a flat plate with a hard-surfacing weld bead deposited on one side, as shown in Fig. 29. The brittle weld is notched to act as a crack starter. The fixture for DWT tests holds the specimen with the notched weld facing downward so that the falling weight will load the specimen in bending. The weld is thus on the tensile surface, and the specimen is backed up so that it can bend only a limited amount (approximately 5°). Well below the NDT, a DWT will produce complete fracture (Fig. 29). Well above the NDT, the specimen will bend elastically and plastically but will not break. The NDT, as defined by this test, is the temperature at which a crack starting at the notched hard-surfacing weld propagates to one or both edges of the tensile surface of the specimen. To conduct a DWT series, specimens are tested over a range of temperatures; the operationally defined NDT is the highest of these temperatures at which the specimen "breaks," according to this definition. The NDT is a widely applied parameter for structural steels and is referenced, for example, in the ASME Boiler and Pressure Vessel Code.

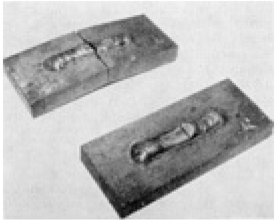


Fig. 29 Fracture appearance of drop weight nil-ductility transition specimens

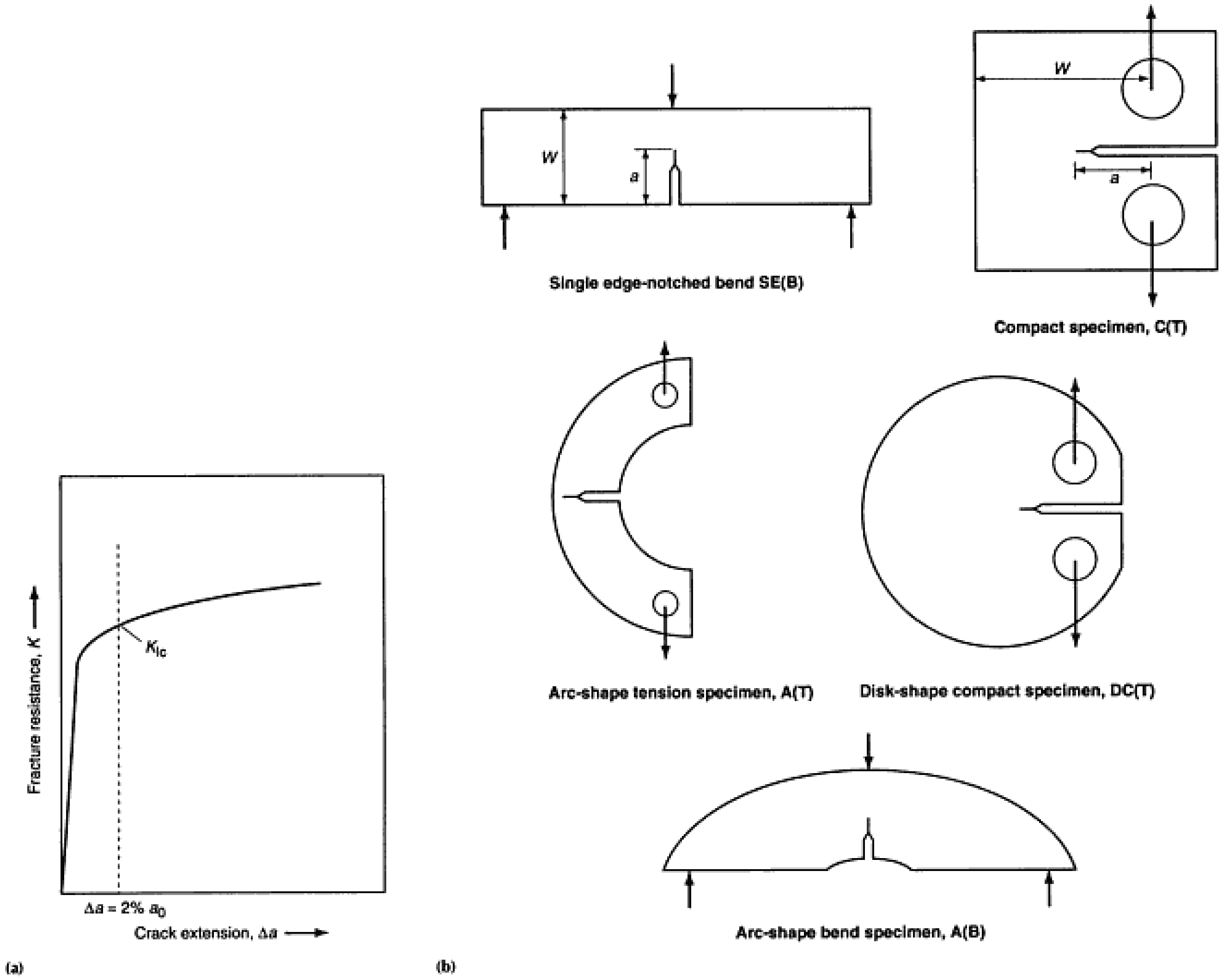
Fracture Toughness Testing

FRACTURE TOUGHNESS is defined as a "generic term for measures of resistance to extension of a crack" (ASTM E 616). The term fracture toughness is usually associated with the fracture mechanics methods that deal with the effect of defects on the load-bearing capacity of structural components. Fracture toughness is an empirical material property that is determined by one or more of a number of standard fracture toughness test methods. In the United States, the standard test methods for fracture toughness testing are developed by the American Society for Testing and Materials (ASTM). These standards are developed by volunteer committees and are subjected to consensus balloting. This means that all objecting points of view to any part of the standard must be addressed. Other industrial countries have equivalent standards writing organizations that develop fracture toughness test standards. In addition, international bodies, such as the International Organization for Standardization (ISO), develop fracture toughness test standards that have an influence on products intended for the intentional market. In this review of fracture toughness testing, the ASTM approach will be emphasized to give the article a consistent point of view.

The standard fracture toughness test methods have been written mostly with metals in mind. Toughness testing of nonmetals is also an important consideration. For many nonmetals, the equivalent standard for metals is adapted with some possible modification. Fracture toughness test methods that are written specifically for a particular nonmetal are mostly in preparation. Therefore, this review emphasizes those standards written for metals without intending to make them apply exclusively to metals.

Fracture Toughness Behavior

Fracture toughness is the resistance to the propagation of a crack. This propagation is often thought to be unstable, resulting in a complete separation of the component into two or more pieces. Actually, the fracture event can be stable or unstable, With unstable crack extension, often associated with a brittle fracture event, the fracture occurs at a well defined point and the fracture characterization can be given by a single value of the fracture parameter. With stable fracture, often associated with a ductile fracture process, the fracture is an ongoing process that cannot be readily described by a point. This fracture process is characterized by a crack growth resistance curve or *R*-curve. This is a plot of a fracture parameter versus the ductile crack extension, Δa. An example *K*-based *R*-curve is shown in Fig. 30(a). Sometimes a single point is chosen on the *R*-curve to describe the entire process; this is mostly done for convenience and does not give a complete quantitative description of the fracture process.



W
a
Single edge-notched bend SE(B)
W
a
Compact specimen, C(T)
Fracture resistance, K
K_{Ic}
Δa = 2% a_0
Crack extension, Δa
Arc-shape tension specimen, A(T)
Disk-shape compact specimen, DC(T)
Arc-shape bend specimen, A(B)
(a)
(b)

Fig. 30 Plane-strain fracture toughness (K_{Ic}) test. (a) Schematic of *K*-based crack resistance (*R*) curve with definition of K_{Ic}. (b) Specimens used in the K_{Ic} test as defined in ASTM E 399

Whether the fracture is ductile or brittle does not directly influence the deformation process that a component or specimen might undergo during the measurement of toughness. The deformation process is generally described as being linear-elastic or nonlinear. This determines which parameter is used in the fracture toughness test characterization. All loading begins as linear-elastic. For this, the primary fracture parameter is the well known crack tip density factor, *K*, originally defined by Irwin. If the toughness is relatively high, the loading may progress from linear-elastic to nonlinear during the toughness measurement, and a nonlinear parameter is needed. The nonlinear parameters that are most often used in toughness testing are the *J*-integral, labeled *J*, and the crack tip opening displacement (CTOD), labeled δ. Because all loading starts as linear-elastic, the nonlinear parameters are all written as a sum of a linear component incorporating *K* and a nonlinear component.

Test Methods

Fracture toughness test methods include linear-elastic and nonlinear loading, slow and rapid loading, crack initiation, and crack arrest. The development of the test methods follows a chronological pattern; that is, a standard was written for a particular technology soon after that technology was developed. Standards written in this matter tend to become exclusive to a particular procedure or parameter. Because most fracture toughness tests use the same specimens and procedures, this exclusive nature of each new standard did not allow much flexibility in the determination of a toughness value. The newer approach is to write standards to encompass all parameters and measures of toughness into a single test procedure. This approach is labeled the common method approach and is being developed by ASTM as well as standards organizations in other countries. The standards for fracture toughness testing are periodically revised, and several new ones are often in development. Volume 3.01 of the *Annual Book of ASTM Standards* should be consulted for the current tests or new test standards.

The fracture toughness test is generally conducted on a test specimen containing a preexisting defect; usually the defect is a sharp crack introduced by fatigue loading and called the precrack. The test is conducted on a machine that loads the specimen at a prescribed rate. Measurements of load and a displacement value are taken during the test. The data resulting from this are subjected to an analysis procedure to evaluate the desired toughness parameters. These toughness results are then subjected to qualification procedures (or validity criteria) to see if they meet the conditions for which the toughness parameters are accepted. Values meeting these qualification conditions are labeled as acceptable standard measures of fracture toughness. The standard fracture toughness test then has these ingredients: test specimens, types, and preparation; loading and instrumentation requirements taken; data analysis; and qualification of results.

Linear-Elastic Fracture Toughness Testing

Fracture mechanics and fracture toughness testing began with a strictly linear-elastic methodology using the crack-tip stress-intensity factor, *K*. Later, nonlinear parameters were developed. However, the first test methods developed used the linear-elastic parameters and were based on *K*. These methods are described first in this article.

Plane-Strain Fracture Toughness (K_{Ic})Test

The first fracture toughness test that was written as a standard was the K_{Ic} test method, ASTM E 399. This test measures fracture toughness that develops under predominantly linear-elastic loading with the crack-tip region subjected to near-plane-strain constraint conditions through the thickness. The test was developed for essentially ductile fracture conditions, but can also be used for brittle fracture. As a ductile fracture test, a single point to define the fracture toughness is desired. To accomplish this, a point where the ductile crack extension equals 2% of the original crack length is identified. This criterion is illustrated schematically with a *K*-*R* curve in Fig. 30(a). This criterion gives a somewhat size-dependent measurement, and so validity criteria are chosen to minimize the size effects as well as restrict the loading to essentially linear-elastic regime. The details of this test can be found in ASTM E 399.

Test Specimen Selection. The first element of the test is the selection of a test specimen. Five different specimen geometries are allowed (Fig. 30b). These are the single edge-notched bend specimen, SE(B); compact specimen, C(T); arc-shape tension specimen, A(T); disk-shape compact specimen, DC(T); and the arc-shape bend specimen, A(B). Many of these specimen geometries are used in the other standards besides ASTM E 399.

The bend and compact specimens are traditional fracture toughness specimens used in nearly every fracture toughness test method. The other three are special geometries that represent special component structural forms. Therefore, most fracture toughness tests are conducted with either the edge-notched bend or compact specimens. The choice between the bend and compact specimen is based on the following:

- The amount of material available (the bend takes more)
- Machining capabilities (the compact has more detail and costs more to machine)
- The loading equipment available for testing

All of the specimens for the K_{Ic} test must be precracked in fatigue before testing.

The choice of the specimen also requires a choice of the size. Because the validity criteria depend on the size of the specimen, it is important to select a sufficient specimen size before conducting the test. However, the validity criteria cannot be evaluated until the test is completed; therefore, choosing the correct size is a guess that may turn out to be wrong. There are guidelines in ASTM E 399 for choosing a correct size, but no guarantee that the chosen size will pass the validity requirement. The test specimen must also be chosen so that the proper material is sampled. This means that the location in the material source and the orientation of the sample must be correct and accounted for. As the specimens are prepared, requirements for tolerances on such things as locations of surfaces, size and location of the notch and pin holes, and surface finishes must be followed.

Loading Machines and Instrumentation. Most tests are conducted on either closed-loop servo-hydraulic machines or a constant-rate crosshead drive machine. The first machine allows load, displacement, or other transducer control, but it is more expensive. It is preferred for precracking, which is usually done at a constant load range so load control is desired. The second type of loading machine is less expensive and may give more stability, but it allows only crosshead control. Because this is required in most of the fracture toughness tests, this type of machine is quite satisfactory for the actual fracture toughness testing but is not so good for precracking.

Loading fixtures must be designed for the test. Two types can be used, choice of loading fixture depends on the test specimen chosen. The bend specimens SE(B) and A(B) use a bend fixture. The tension specimens C(T), DC(T), and A(T) require a pin-and-clevis loading.

For the K_{Ic} test, a continuous measurement of load and displacement is required during the test. The load is measured by a load cell, which should be on all loading machines. The measurement of displacement is usually done with a strain-gaged clip gage that is positioned over the mouth of the crack in the specimen. The ASTM E 399 standard gives guidelines for the working requirements of the load and displacement gages used in the tests.

The loading of the specimen is done at a prescribed rate. It must be done fast enough so that any environmental or temperature interactions are not a problem. On the other hand, it must be done slowly enough so that it is not considered a dynamically loaded test. For the K_{Ic} test, the load must be applied at a rate so that the increase in K is given by the range 0.55 to 2.75 MPa$\sqrt{\text{m}}$/s. The loading is done in displacement control, which usually means test machine crosshead control. During the loading, the load and displacement are measured continuously either autographically or digitally.

Test Data and Analysis. The load-and-displacement record provides the basic data of the test. The data are then analyzed to determine a provisional K_{Ic} value labeled K_Q. This provisional value is determined from a provisional load, P_Q, and the crack length. The P_Q value is determined with a secant slope on the load-and-displacement record (Fig. 31). The P_Q value determined by drawing the original loading slope of the load-versus-displacement record. A slope of 5% less than the original slope is then drawn from the origin. For a monotonically increasing load, the P_Q is taken where the 5% secant intersects the load-versus-displacement curve, this is shown as type I in Fig. 31. For other records in which an instability or other maximum load is reached before the 5% secant, the maximum load reached up to and including the possible intersection of the 5% secant is the P_Q. Type II shown in Fig. 31 is an example of one of the other types of load-versus-displacement records. The 5% secant corresponds to about 2% ductile crack extension; this may be physical crack extension or effective crack extension related to plastic zone development. Unstable failure before reaching the 5% offset also marks a measurement point for P_Q at the maximum load reached at the point of instability.

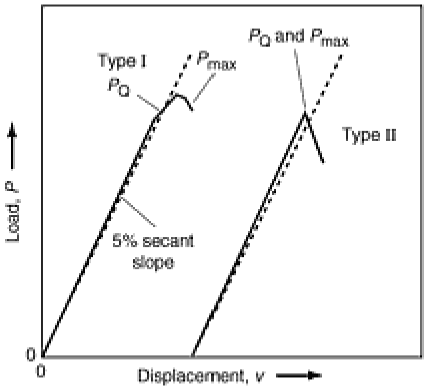


Fig. 31 Typical load-versus-displacement record for the K_{Ic} test, two types

The P_Q value is used to determine the corresponding K_Q value, which is calculated:

$$K = P\, f(a/W)/B\sqrt{W}$$

where P is load, B and W are specimen thickness and width, and $f(a/W)$ is a calibration function that depends on the ratio of crack length to specimen width, a/W, and is given in the standard. For the calculation of K, a crack length value, a, is required. This comes from a physical measurement on the fracture surface of a broken specimen half. The specimen must be fractured into halves if it is not already that way from the test. The crack length is measured to the tip of the precrack using an averaging formula in the test standard. This value of crack length normalized with width, W, is used in the calibration function $f(a/W)$ to determine the K_Q value.

The K_Q is provisional K value that may be the K_{Ic} if it passes the validity requirements. The two major validity requirements are to ensure that crack resistance does not increase significantly with crack growth and that linear-elastic loading and plane-strain thickness are achieved. The first of these two requirements is quantified:

$$\frac{P_{\max}}{P_Q} \leq 1.10$$

which limits the R-curve behavior to an essentially flat trend and ensures that some physical crack extension. The second requirement is:

$$a, B \geq 2.5\left(\frac{K_Q}{\sigma_{ys}}\right)$$

which guarantees linear-elastic loading and plane-strain thickness, $P_{\max}$ is the maximum value of load reached during the test. An example of $P_{\max}$ is shown in Fig. 31; σ_{ys} is the 0.2% offset yield strength. Values of K_Q that pass these validity requirements are labeled as valid K_{Ic} and are reported as such in a standard prescribed reporting of test results.

Fatigue precracking should be done in accordance with ASTM E 399. The K level used for precracking each specimen should not exceed about two-thirds of the intended starting K-value for a given environmental exposure. This prevents fatigue damage, or residual compressive stress at the crack tip, which may alter the fracture toughness behavior, particularly when testing at a K-level near the K_Q value for the specimen.

Chevron notches are sometimes used to facilitate starting such mechanical precracks. These modifications also may be necessary to control fatigue precracking of some materials.

Rapid-Load $K_{Ic}(t)$

A value of fracture toughness labeled $K_{Ic}(t)$ can be determined for a rapid-load test. Details of this method are given in a special annex to the method E 399. For the static loading rate K_{Ic} value, the maximum loading rate is defined as 2.75 MPa$\sqrt{\text{m}}$/s. Anything faster than that is labeled as a rapid-load fracture toughness. The specimen apparatus and procedure are much the same as for the regular K_{Ic} test. Special instructions are given to ensure that the instrumentation can handle the rapidly changing signals. The interpretation of results must be based on a dynamic value of the yield stress, σ_{YD}. An equation for σ_{YD} is given in the Annex to E 399. Results are reported $K_{Ic}(t)$, where the loading time of the test is written in parentheses after the measured toughness value.

K-R Curve (ASTM E 561)

Ductile fracture toughness behavior is measured by a crack growth resistance curve or "R-curve," which is defined as "a plot of crack-extension resistance as a function of slow-stable crack extension." Although many ductile fracture processes can be measured as a single point, such as with K_{Ic}, the R-curve is a more complete description of the fracture toughness. When the R-curve increases significantly, a single-point measurement is even less descriptive of the actual fracture toughness. Steeply rising R-curves occur in many metallic materials but especially in thin plate or sheet materials. The steeply rising *R*-curve makes the single-point definition more size- and geometry-dependent and does not lend to structural evaluation.

The *K*-*R* curve is a good method for fracture toughness characterization in cases where the *R*-curve is steeply rising but the fracture behavior occurs under predominantly linear-elastic loading conditions. The *K*-*R* curve procedure is given by ASTM E 561. The objective of the method is to develop a plot *K*, the resistance parameter, versus effective crack extension, Δa_e.

The method allows three different test specimens: the compact, C(T); the center-cracked tension panel, M(T); and the crack-line-wedge-loaded specimen, C(W). The compact specimen is the same as the compact type in ASTM E 399 for K_{Ic} tests (Fig. 30b). The center-cracked tension panel and the crack-line-wedge-loaded specimens are shown in Fig. 32(a) and 32(b), respectively. The first two specimens use a conventional loading machine with fixtures that are specified in the test method. The C(W) specimen is wedge loaded to provide a stiff, displacement-controlled loading system (Fig. 32b). The can prevent rapid, unstable failure of the specimen under conditions where the *R*-curve toughness is so low that the *R*-curve can be measured to larger values of Δa_e. All specimens must be precracked in fatigue.

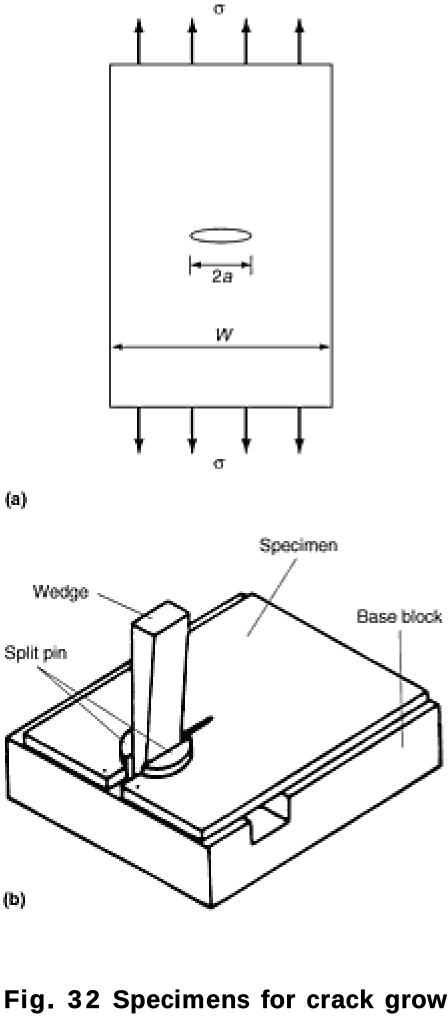


Fig. 32 Specimens for crack growth resistance testing. (a) Center-cracked tension specimen, M(T). (b) Crack-line-wedge-loaded compact specimen, C(W), in loading fixture

The instrumentation required on the specimens is similar to that for the K_{Ic} test, except for the case of the C(W) specimen. The basic test result is a plot of load versus displacement measured across the specimen mouth. From this, an effective crack length is determined from secant offset slopes to the load-versus-displacement record (Fig. 33). An effective crack extension is the difference between the original and effective crack lengths. Effective crack length is determined from the slope of the secant offset using the appropriate compliance function, which relates this slope to crack length. The *K* is determined as a function of the load and corresponding effective crack length:

$$K = Pf(a_e/W)/B\sqrt{W}$$

The resulting plot of K versus effective crack length is the desired K-R curve fracture toughness. The result is subjected to a validity requirement that limits the amount of plasticity. For the C(T) and C(W) specimens:

$$b = (W - a) \geq (4/\pi)(K_{max}/\sigma_{ys})^2$$

where b is the uncracked ligament length, σ_{ys} is the 0.2% offset yield strength, and K_{max} is the maximum level of K reached in the test. For the M(T) specimen, the net section stress based on the physical crack size must be less than the yield strength.

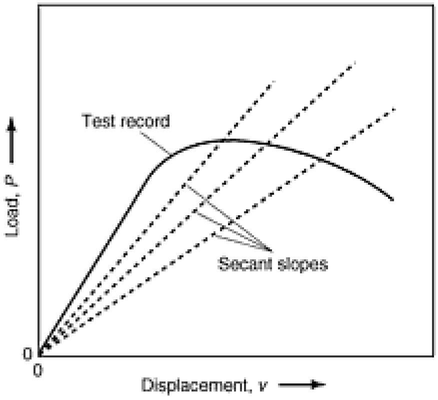


Fig. 33 Secant offset measurement of effective crack length

For the C(W) specimen, a load is not measured. The data collected are a series of displacement values taken at two different points along the crack line, one near the crack mouth and one nearer the crack tip. From the two different displacement values, an effective crack length can be determined from the ratio of the two displacement values and from calibration values given in a table in E 561. From the crack length and displacement, a K-value can be determined and the K-R curve constructed. The toughness result is then a curve of K versus Δa_e, somewhat similar to the one in Fig. 30.

Crack Arrest, K_{Ia}(ASTM E 1221)

This procedure allows a toughness value to be determined based on the arrest of a rapidly growing crack, which may be lower than the initiation value. The specimen and procedure are somewhat different from the previously discussed toughness test methods that determine initiation toughness values only. The specimen for crack arrest testing is called the compact-crack-arrest compact specimen (Fig. 34). It is similar to the crack-line-wedge-loaded specimen, C(W), of the K-R curve method and requires wedge loading in order to provide a very stiff loading system to arrest the crack. The notch preparation is different from the other standards in that the specimen has a notch with no precrack. Generally, a brittle weld bead is placed at the notch tip to start the running crack, although other methods are allowed. The running crack advances rapidly into the test material and must be arrested by the test material to produce a K_{Ia} result. The only instrumentation on the specimen is a displacement gage. A load cell is placed on the loading wedge, but it does measure the load on the specimen. The displacements at the beginning of the unstable crack extension and at the crack arrest position are measured and converted to K values. To eliminate effects of non-linear deformation, which cannot be directly measured with only a displacement gage, a series of loads and unloads are conducted on the specimen until the unstable cracking occurs. When the specimen is unloaded, the crack tip can be marked by a procedure called "heat tinting." Heat tinting consists of marking the physical crack extension by heating the specimen until oxidation occurs on the crack. The specimen is then broken open, and the crack extension measured on the fracture surface.

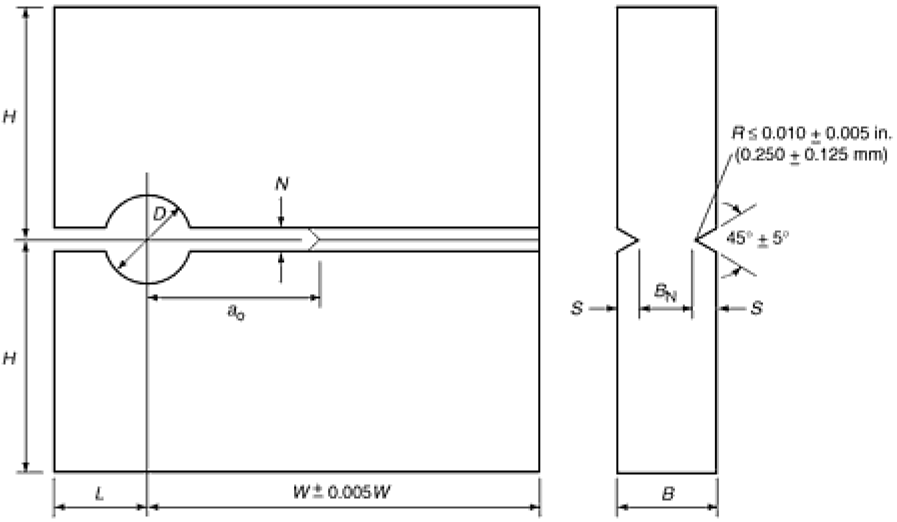


Fig. 34 Crack-line-wedge-loaded compact-crack-arrest specimen

The value of K_{Ia} is determined from a displacement value and the crack length at the arrest point. Validity is determined from the size criterion:

$$W - a \geq 1.25(K/\sigma_{YD})^2$$

where σ_{YD} is a dynamic yield strength. To complete a successful K_{Ia} test, careful attention must be paid to the instructions in E 1221.

Nonlinear Fracture Toughness Testing

Linear-elastic parameters are used to measure fracture toughness for relatively low toughness materials that fracture under or near the linear loading portion of the test. For many materials used in structures, it is desirable to have high toughness, a value at least high enough so that the structure would not reach fracture toughness before significant yielding occurs. For these materials, it is necessary to use the nonlinear fracture parameters to measure fracture toughness properties. The two leading nonlinear fracture parameters are J and δ. For high toughness materials, fracture is often by a ductile mechanism, but this is not necessarily the case for all materials.

J_{Ic} Testing (ASTM E 813). One of the first tests developed using the J parameter is the J_{Ic} test per ASTM E 813. In this test, an R-curve is developed using J versus Δa pairs and a point near the beginning of the R curve is defined as J_{Ic} "a value of J near the onset of stable crack extension" (ASTM E 813). The specimens for the J_{Ic} test are the bend SE(B) and compact C(T). These specimens are similar to the ones used for K_{Ic} testing; however, the compact specimen for J testing has a cutout on the front face so that a displacement gage can be mounted directly on the load line; that is, in the line of the applied loads. The loading fixtures required are the bend fixture for the bend and the pin-and-clevis for the compact. Again, a clevis with a loading flat at the bottom of the pin hole in the clevis is essential to get free rotation of the specimen. The instrumentation required is the load cell and a displacement measuring clip gage. If the electrical potential system is used additional instrumentation is required. The clip gage for the J_{Ic} test requires more resolution than that for the K_{Ic} test if a single specimen test method is used. For the bend specimen, a loadline clip gage is needed to measure J. Additionally, a second clip gage can be used over the crack mouth if a single specimen method is used.

The basic output of the test is a plot of J versus physical crack extension (Δa). (Unlike the K-R curve method, which uses effective crack extension, the J_{Ic} test uses physical crack extension.) To obtain the required J versus Δa data measurements of load, displacement and physical crack length are required during the test. There are two techniques used to develop these data. The first is the multiple-specimen test method, in which each specimen develops a single value of J and Δa but no special crack monitoring equipment is needed during the test. Crack extension is measured on the fracture surface at the conclusion of the test. However, for this technique a number of specimens are required to develop the plot of J versus Δa values needed for the result. The other method is the single specimen test from which all the J versus Δa

values are developed from one test. To accomplish this, a method of crack length monitoring is needed during the test. The primary method for crack length monitoring during the test is called the elastic unloading compliance method, in which crack length is measured from an elastic slope. The measurement of the elastic slope requires only a clip gage that measures displacement. The compact specimen uses the gage mounted on the load line. The bend specimen could use two gages: one on the loadline to measure *J* and one over the crack mouth to measure slope. The second single-specimen method is the electrical potential crack monitoring system, in which the electrical resistivity of the specimen is measured and correlated with crack length during the test. This is a secondary method to measure crack length and is not described in detail in the E 813. It requires some additional expertise on the part of the tester to use.

The test procedure depends on the method of crack length monitoring. For the multiple-specimen test, five or more specimens are loaded to prescribed displacement values that are thought to give some physical crack extension but not complete separation of the specimen. This results in a number of individual load-versus-displacement records, as shown in Fig. 35. When the prescribed displacement is reached, the specimen is unloaded and the crack tip is marked by heat tinting.

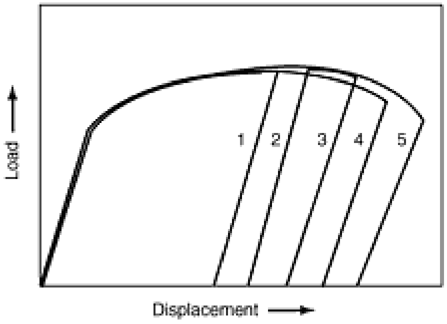


Fig. 35 Load versus displacement for multiple-specimen tests

The single-specimen method using elastic compliance is initially loaded in the same way; however, during the test partial unloadings are taken to develop elastic slopes from which crack length can be evaluated using compliance relationships (Fig. 36). The compliance relationships are given in E 813. For the electrical potential method, the load, displacement, and potential change are measured simultaneously. Potential changes are related to crack length through either an analytical or empirical correlation.

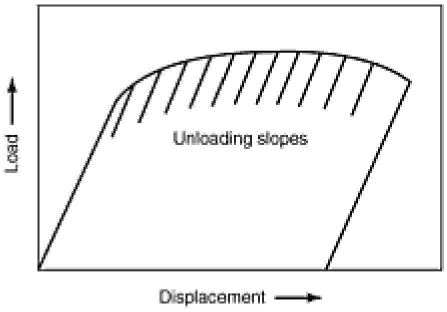


Fig. 36 Load versus displacement with unloading slopes

From these test results, *J* is evaluated from the load-versus-loadline displacement record. The *J* is calculated from a linear combination of an elastic term and a plastic term:

$$J = J_{el} + J_{pl} = \frac{K^2(1 - \nu^2)}{E} + \frac{\eta_{pl}}{Bb} \int_0^{\nu_{pl}} P \, d\nu_{pl}$$

where K is the stress-intensity factor, E is elastic modulus, ν is Poisson's ratio, P is load, ν_{pl} is plastic displacement, B is specimen thickness, b is specimen uncracked ligament ($W - a$, where W is specimen width), and $\eta_{pl} = 2 + 0.522b/W$ for the compact specimen. This equation is the basic J formula for the case of a nongrowing crack. It is based on a K equivalence for the elastic component of J and an area term for the plastic component of J. Alternate J formulas are given in E 813 for the growing crack. The crack length is used to determine $\Delta a = a - a_0$, where a_0 is the original crack length at the beginning of the test.

The J versus Δa results form a part of the J-R curve and are the basic data of the J_{Ic} method. The objective is to get J versus Δa values in a certain restricted range. These data are then subjected to a prescribed evaluation scheme to choose a point on the J-R curve that is near the initiation of stable cracking. The method for developing the J_{Ic} is somewhat complicated, and the details are given in E 813. Basically, the J versus Δa pairs are evaluated to see which fall in a prescribed range. The pairs falling in the correct range are fitted with a power-law equation:

$$J = C_1(\Delta a)^{C_2}$$

where C_1 and C_2 are constants. A construction line is drawn, and the intersection of this with the fitted line is the evaluation point for a candidate J_{Ic} value. This candidate value is labeled J_Q.

The candidate J_Q value is subjected to qualification criteria to see if it comprises an acceptable value. The basic one is to guarantee a sufficient specimen size:

$$b,B \geq 25(J_Q/\sigma_Y)$$

where σ_Y is an effective yield strength and

$$\sigma_Y = (\sigma_{ys} + \sigma_{uts})/2$$

where σ_{ys} and σ_{uts} are the yield strength and ultimate tensile strength, respectively. If the qualification requirements are met, the J_Q is J_{Ic}, and the results are reported following the prescribed format in E 813. A more complete evaluation of fracture toughness for ductile fracture based on J is the J-R curve procedure in ASTM E 1152. This standard uses the same specimens, instrumentation, and test procedures as the J_{Ic} test. The J_{Ic} and J-R curve methods are very similar, hence a combined J standard is being prepared.

Crack Tip Opening Displacement (CTOD) (ASTM E 1290). The crack tip opening displacement method of fracture toughness measurement was the first one that used a nonlinear fracture parameter to evaluate toughness. The first CTOD standard was written by the British Standards Institution (BS 5762, 1979). Subsequently, ASTM E 1290 was written as the U.S. version of this test method. The basic idea of the test method is to evaluate a fracture toughness point for brittle fracture or to evaluate a safe point for the case of ductile fracture. The primary measurements of toughness are at unstable fracture before significant ductile crack extension, labeled δ_c; unstable fracture after significant crack extension, δ_u; or the point of maximum load in the test, δ_m. The method originally had a point near the beginning of stable crack extension, δ_i, that was measured as a point on an R-curve in a similar manner to J_{Ic}. This point was subsequently removed from the test method.

The CTOD standard uses the same bend and compact specimens that are used in the J_{Ic} test; thus, the same loading fixtures are used. The method requires measurement of load and displacement during the test. The formulas for δ calculation use a combination of an elastic and a plastic component for δ:

$$\delta = K^2(1 - \nu^2)/2\ \sigma_{ys}E + r_p(W - a_0)\nu_p/[r_p(W - a) + a_0 + z]$$

In this equation, the elastic component of δ is based on an equivalent K and the plastic component is based on a rigid plastic rotation of the specimen about a neutral stress point at $r_p(W - a_0)$ from the crack tip. In the equation, ν is Poisson's ratio, σ_{ys} is the yield strength, r_p is a rotation factor, ν_p is a plastic component of displacement, $W - a_0$ is the uncracked ligament length, and z is the position of the clip gage from the crack measurement position.

For many years, the CTOD test was the only one that measured toughness for a brittle, unstable fracture event using a nonlinear fracture parameter. In addition, the method allows the measurement of toughness after a "popin," which is described as a discontinuity in the load-versus-displacement record usually caused by a sudden, unstable advance of the crack that is subsequently arrested.

New Test Methods

The development of standard fracture toughness test methods is an ongoing process. Some new test methods for fracture toughness testing include:

- The combined *J* standard (ASTM E 1737-96)
- The common test method (ASTM E 1820-96)
- The transition fracture toughness standard
- The standard for testing of weldments

The latter two methods will likely become test standards in the near future.

Fatigue Life Testing

FATIGUE TESTS can be classified as crack initiation or crack propagation tests. In crack initiation testing, specimens or parts are subjected to the number of stress (or strain-controlled) cycles required for a fatigue crack to initiate and to subsequently grow large enough to produce failure. In crack propagation testing, fracture mechanics methods are used to determine the crack growth rates of pre-existing cracks under cyclic loading. Both methods can be used in a benign environment, or by the combined effects of cyclic stresses and an aggressive environment (corrosion fatigue).

This section focuses on fatigue life test methods and general fatigue life data. In general, fatigue life (crack initiation) testing is stress controlled (SN) or strain controlled (ε-N). The test specimens (Fig. 37) are described primarily by the mode of loading, such as direct (axial) stress, plane bending, rotating beam, alternating torsion, and combined stress.

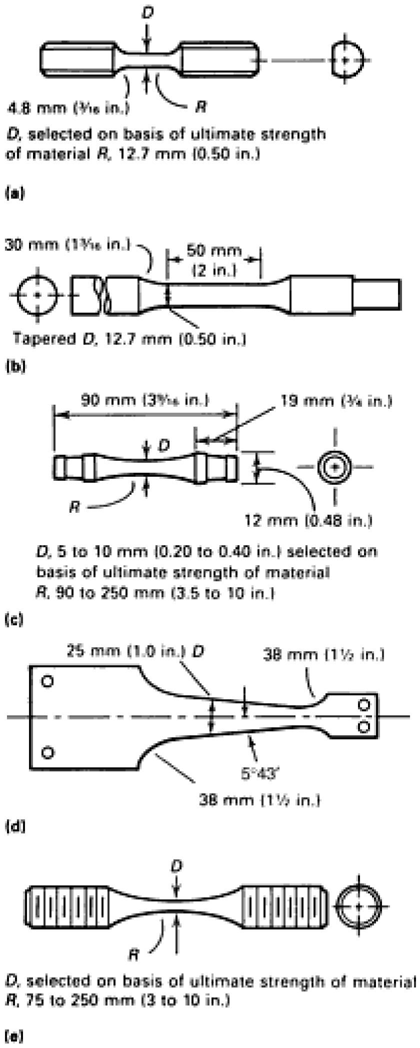

D
4.8 mm (3/16 in.)
R
D, selected on basis of ultimate strength of material R, 12.7 mm (0.50 in.)
(a)
30 mm (1 3/16 in.)
50 mm (2 in.)
Tapered D, 12.7 mm (0.50 in.)
(b)
90 mm (3 9/16 in.)
19 mm (3/4 in.)
D
R
12 mm (0.48 in.)
D, 5 to 10 mm (0.20 to 0.40 in.) selected on basis of ultimate strength of material
R, 90 to 250 mm (3.5 to 10 in.)
(c)
25 mm (1.0 in.) D
38 mm (1 1/2 in.)
5°43'
38 mm (1 1/2 in.)
(d)
D
R
D, selected on basis of ultimate strength of material
R, 75 to 250 mm (3 to 10 in.)
(e)

Fig. 37 Typical fatigue life test specimens. (a) Torsional specimen. (b) Rotating cantilever beam specimen. (c) Rotating beam specimen. (d) Plate specimen for cantilever reverse bending. (e) Axial loading specimen. The design and type of specimen used depend on the fatigue testing machine used and the objective of the fatigue study. The test section in the specimen is reduced in cross section to prevent failure in the grip ends and should be proportioned to use the upper ranges of the load capacity of the fatigue machine (i.e., avoiding very low load amplitudes where sensitivity and response of the system are decreased).

Test Methods

Testing machines are defined by several classifications: the controlled test parameter (load, deflection, strain, twist, torque, etc.); the design characteristics of the machine (direct stress, plane bending, rotating beam, etc.) used to conduct the specimen test; or the operating characteristics of the machine (electromechanical, servohydraulic, electromagnetic, etc.). Machines range from simple devices that consist of a cam run against a plane cantilever beam specimen in constant-deflection bending to complex servohydraulic machines that conduct computer-controlled spectrum load tests.

Axial and rotating-bending machines are most commonly used for fatigue tests. Surface preparation of specimens is critical in all fatigue life tests.

Axial Fatigue Life Tests. ASTM E 466 specifies specimens to be used in axial fatigue tests. The specific dimensions of specimens depend on the objective of the experimental program, machine to be used, and available material. ASTM does not specify dimensions but details preparation techniques and reporting techniques. In reporting, a sketch of the specimen, with dimensions, should be given. The surface-roughness and out-of-flatness dimensions should be included. Specimens should not be subjected to any surface treatment.

For axial loading, ASTM E 466 states that regardless of the machining, grinding, or polishing method used, the final metal removal should be in a direction approximately parallel to the longitudinal axis of the specimen. Improper preparation methods can greatly bias the results. Hence, preparation techniques should be carefully developed; if a change in the preparation technique is made, it has to be demonstrated that it does not introduce any bias in the results.

Rotating-bending fatigue tests of the simple beam type are performed in testing machines such as that shown in Fig. 38, sometimes called the R.R. Moore testing machine. In operation, an electric motor rotates a cylindrical specimen, usually at 1800 rpm or higher, while a simple mechanical counter records the number of cycles. Loads are applied to the center of the specimen by a system of bearings and dead weights. A limit switch stops the test when the specimen breaks and the weights descend.

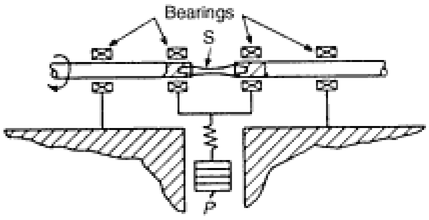


Fig. 38 Loading arrangement for a rotating-beam fatigue-testing machine. S, specimen; *P*, load

The weights produce a moment that causes the specimen to bend. A strain gage placed on the specimen shows compressive stresses on the top and tensile stresses when the gage is rotated to the bottom. Stresses range from maximum tension to maximum compression during each revolution of the testing machine.

Bending moments can be converted to stress by assuming that they are elastic and by employing the flexure formula:

$$\sigma = MC/I$$

For circular specimens, $I = \pi C^4/4$, where C is the specimen radius. The maximum stress at the outer fiber, σ, is proportional to the bending moment, M. This moment is the product of the moment arm and the force.

The specimen is machined from the material to be tested and is fastened into the bearing housing with special cap screws. The effective dead weight of the R.R. Moore machine and weighing apparatus is 4.54 kg (10 lb), which is deducted from the total weight required and added to the weight pan (Fig. 38) to provide the desired stress:

$$18.22 \text{ kg} - 4.54 \text{ kg} = 13.68 \text{ kg}$$
$$(40.13 \text{ lb} - 10 \text{ lb} = 30.13 \text{ lb})$$

When the drive motor is actuated, a counter records the number of revolutions. If the specimen breaks, the bearing housing descends and actuates a switch that shuts off the drive motor. If the specimen does not break (carbon and low-alloy steels may achieve a million or more cycles), the stress is at or below the endurance limit. Next, the machine is shut off and another specimen is run at a higher stress level. A series of tests is performed to provide sufficient data at varying stress levels.

For cantilever-beam rotating-bending machines of the White-Souther type (Fig. 39), a different bending moment is used in stress calculation. A weight, P, is supported by fixture to a ball-bearing housing at the free end of the specimen. This produces a bending moment, M, that equals $P \times L$, which is the distance of the specimen from the center of the applied load, 75 mm (3 in.). The stress in the outer fiber is

$$S = \frac{PL}{Ic}$$

The weight added to the weight pan is the calculated weight minus the weight of the weighing apparatus.

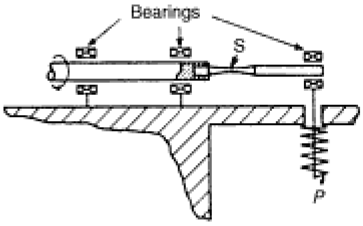


Fig. 39 Loading arrangement for a cantilever-beam fatigue machine for rotating-bending testing. S, specimen; *P*, load

Plate-Bending Machines. In rotating-bending tests, the mean or average stress is always zero. The effect of mean stress, which is very important in fatigue, is evaluated by cantilever bending machines that are used to test plate materials. In these machines, sometimes called Kraus plate-bending machines, specimens are loaded with constant deflection by means of an eccentric crank (Fig. 40). Stresses can be calculated by assuming that they are elastic. In many cases this is not a good assumption, because, when tested, some soft materials may involve small amounts of plastic stress.

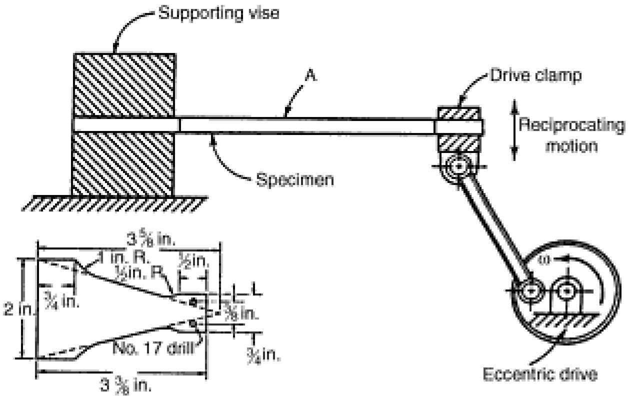


Fig. 40 Reciprocating-bending fatigue-testing machine, and typical specimen (at lower left) for testing of sheet

Specimens are usually tapered to provide a constant-stress test area. The approximate stress, *S*, is given by:

$$S = \frac{ytE}{l^2}$$

where *y* is the specimen deflection, *t* is the thickness of the specimen, *E* is the elastic modulus, and *l* is the distance from load application to the back of the specimen. Constant-deflection beam-type machines are used to test both strip and plate. A typical specimen is shown at lower left in Fig. 40.

Resonant-Testing Machines. Machines for resonant testing are basically spring-mass, vibrating systems. The frame design is based on a resonant, spring-mass system that consists of two masses linked by the specimen and grip string and that oscillates as a dipole. The system is excited by an electromagnet housed in the machine base. The masses and load string are positioned in the vertical frame, which is suspended and guided on leaf springs. The eight springs are arranged in a special configuration to make a unique and compact design without the need for a heavy seismic block.

Mean load is applied by a motor located in the base of the system. The motor drives the four comer gearboxes through two shafts and applies mean loads in both tension and compression. The mean-load force is carried by the box-type structure of springs, and the level either is adjusted by a hand-held controller or is maintained at a level preset by the controller. The magnet air gap is maintained automatically by the action of the gap servomotor driving a wedge beneath the electromagnet. A linear variable displacement transformer (LVDT) constantly monitors the air gap, and control is maintained even when the mean load is changed while the machine is running. A manually operated drive located in the upper mass permits major adjustment of specimen spacing.

The electromagnet excites the dual-mass system at its natural frequency by means of pulse excitation. This feature enables a simple switch to replace the conventional power amplifier, thus providing high reliability at low cost and, in addition, eliminating the need to tune an oscillator to the natural frequency of the system. Closed-loop amplitude control is achieved by controlling the pulse power to the magnet from the error between the actual and demanded load amplitudes, thereby providing fast response to changing load demands. A strain-gaged load cell provides accurate load monitoring and digital indication of peak dynamic load, mean load, and frequency.

Ultrasonic fatigue testing involves cyclic stressing of material at frequencies typically in the range of 15 to 25 kHz. The major advantage of using ultrasonic fatigue is its ability to provide near-threshold data within a reasonable length of time. High-frequency testing also provides rapid evaluation of the high-cycle fatigue limit of engineering materials as described in the article "Ultrasonic Fatigue Testing" in *Mechanical Testing*, Volume 8, *Metals Handbook*, 9th edition.

Corrosion Fatigue Life Testing. High-cycle corrosion fatigue tests (performed in the range of 10^5 to 10^9 cycles to failure) are typically done at a relatively high frequency of 25 to 100 Hz to conserve time. Multiple, inexpensive rotating-bend machines are often dedicated to these experiments. Low-cycle corrosion fatigue tests (in the regime where plastic strain, ε_p, dominates) follow from the ASTM standard for low-cycle fatigue testing in air (ASTM E 606).

For aqueous media, the typical cell for corrosion fatigue life testing includes an environmental chamber of glass or plastic that contains the electrolyte. The specimen is gripped outside of the test solution to preclude galvanic effects. The chamber is sealed to the specimen, and solution can be circulated through the environmental cell. The setup should include reference electrodes and counter electrodes to enable specimen (working electrode) polarization with standard potentiostatic procedures. Care should be taken to uniformly polarize the specimen, to account for voltage drop effects, and to isolate counter electrode reaction products. If potential is controlled, control of the oxygen content of the solution may not be necessary, although highly deaerated solutions are considered prudent.

Environmental containment for high-cycle and low-cycle corrosion fatigue life testing is similar, but the overall setup for low-cycle (strain-controlled) testing is more complicated because gage displacement must be measured. For strain-controlled fatigue life, testing in simple aqueous environments, diametral or axial displacement is measured by a contacting but galvanically insulated extensometer, perhaps employing pointed glass or ceramic arms extending from an extensometer body located outside of the solution. Hermetically sealed extensometers or linear-variable-differential transducers can be submerged in many electrolytes over a range of temperatures and pressures. Alternately, the specimen can be gripped in a horizontally mounted test machine and be half submerged in the electrolyte with the extensometer contacting the dry side of the gage. For simple and aggressive environments, grip displacement can be measured external to the cell-contained solution, such as for high-temperature water in a pressurized autoclave. It is necessary to conduct low-cycle fatigue tests in air (at temperature), with an extensometer mounted directly on the specimen gauge, to relate grip displacement and specimen strain.

Fatigue Life Data

It has long been recognized that fatigue data, when resolved into elastic and plastic terms, can be represented as linear functions of life on a logarithmic scale. Figure 41 schematically shows this representation of elastic and plastic components, which together define the total fatigue life curve of a material. The general fatigue-life relation, expressed in terms of the strain range ($\Delta\varepsilon$, where $\Delta\varepsilon$ is the strain change from cyclic loading), is as follows:

$$\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p \qquad \textbf{(Eq 27)}$$

where $\Delta\varepsilon_e$ is the elastic strain range, $\Delta\varepsilon_p$ is the plastic strain range, and where:

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma'_f}{E}(2N_f)^b \qquad \textbf{(Eq 28)}$$

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon'_f\ (2N_f)^c \qquad \textbf{(Eq 29)}$$

Therefore, the total strain amplitude (or half the total strain range, $\Delta\varepsilon/2$) can be expressed as the sum of Eq 28 and 29:

$$\frac{\Delta\varepsilon}{2} = \varepsilon'_f(2N_f)^c + \frac{\sigma'_f}{E}(2N_f)^b \qquad \textbf{(Eq 30)}$$

where ε'_f is the fatigue ductility coefficient, σ'_f is the fatigue strength coefficient, *b* is the fatigue strength exponent, *c* is the fatigue ductility exponent, and N_f is the number of cycles to failure.

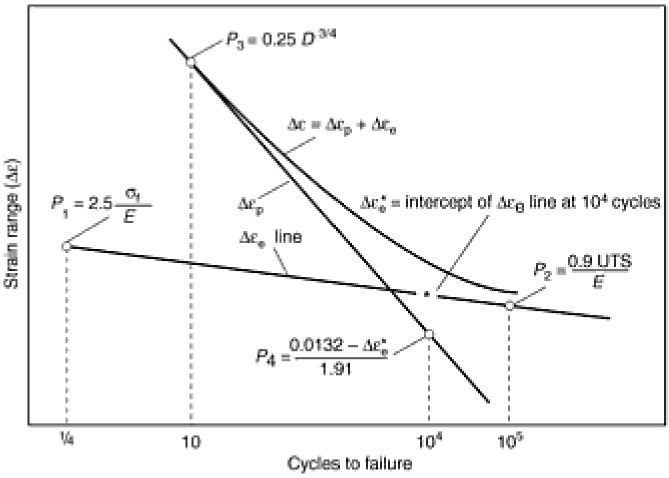


Fig. 41 Schematic of fatigue life curve with the Manson four-point criteria for the elastic and plastic strain lines. *D* is the tensile ductility, σ_f is the fracture stress (load at fracture divided by cross-sectional area after fracture), and UTS is conventional ultimate tensile strength.

These four empirical constants (b, c, σ'_f, ε'_f) form the basis of modeling strain-life behavior for many alloys, although it must be noted that some materials (such as some high-strength aluminum alloys and titanium alloys) cannot be represented by Eq 30.

For many steels and other structural alloys, substantial data have been collected for the four parameters in Eq 30. In many cases, the four fatigue constants have been defined by curve fitting of existing fatigue life data. A collection of this data is tabulated in *Fatigue and Fracture,* Volume 19, *ASM Handbook.*

The four fatigue constants can also be estimated from monotonic tensile properties. With the availability of extensive data, however, these techniques are not widely used. Nonetheless, the "four-point method" is a method to estimate fatigue life behavior from tensile properties. This method can be used to compare fatigue and tensile properties.

In addition, it should also be mentioned that the four fatigue constants are also related to the following parameters:

$$K' = \frac{\sigma'_f}{(\varepsilon'_f)^{n'}} \quad \textbf{(Eq 31)}$$

$$n' = b/c \quad \textbf{(Eq 32)}$$

where K' is the cyclic strength coefficient and n' is the cyclic strain hardening exponent in the power-law relation for a log-log plot of the completely reversed stabilized cyclic true stress (σ) versus true plastic strain (ε_p), such that $\sigma = K'(\varepsilon_p)^{n'}$. The use of power-law relationship is not based on physical principles, although the relationships in Eq 31 and 32 may be convenient for mathematical purposes. The parameters K' and n' are usually obtained from a curve fit of cyclic stress-strain data.

Four-Point Method

Numerous studies have been devoted to the development of techniques for estimating strain-controlled fatigue characteristics (per Eq 30). For the most part, these studies dealt with data generated under completely reversed strain cycling (i.e., $R = -1$, or $A = \infty$) and usually attempted to relate fatigue properties with tensile properties. Extensions of these studies have carried the estimating procedures a step further, addressing the correlation of fatigue data obtained at various strain ratios (R).

Two common methods for approximating the shape of a fatigue curve are the "method of universal slopes" and the "four-point correlation" method. These two methods have been known for many years. The method of universal slopes, first proposed by Manson, is based on the relation:

$$\Delta\varepsilon \doteq 3.5 \frac{\text{UTS}}{\text{E}} (N_f)^{-0.12} + \varepsilon_f^{0.6} (N_f)^{-0.6} \quad \textbf{(Eq 33)}$$

where UTS is ultimate strength, E is modulus of elasticity, and ε_f is true fracture ductility, or ln [1/(1 - RA)].

This approximation thus requires only tensile strength, modulus, and reduction in area (RA). However, note that it is based on strain range ($\Delta\varepsilon$) rather than strain amplitude ($\Delta\varepsilon/2$).

The four-point method also allows construction of fatigue life curves from more readily available handbook data (i.e., monotonic tensile data). This method can be compared with the traditional strain-based approach (Fig. 41) or a stress-based approach. In both cases, the four-point method is based on the premise that total fatigue life per Eq 30 can be estimated as the sum of elastic strain (Eq 28) and plastic strain (Eq 29) components. The step-by-step process for locating points on the plastic- and elastic-strain-life lines is described below for both strain-based and stress-based data.

Strain-Based Four-Point Method. The four-point method initially was developed in terms of strain range by Manson (Fig. 41). The four points in Fig. 41 are determined as follows:

- *Point P_1 on the elastic strain line* is positioned at $N_f = 0.25$ cycles (where a monotonic test is $\frac{1}{4}$ of one fatigue cycle) and at an elastic strain range of $2.5\ \sigma_f/E$ (where σ_f is the fracture stress in a tensile test and E is the elastic modulus).
- *Point P_2 on the elastic strain line* is positioned at $N_f = 10$ cycles and at an elastic strain range of 0.9 UTS/E, where UTS is the conventional ultimate tensile strength.
- *Point P_3 on the plastic strain line* is positioned at $N_f = 10$ cycles, where the plastic strain range is $0.25D^{3/4}$ and D is the conventional logarithmic ductility (also known as ε_f).
- *Point P_4 on the plastic strain line* is positioned at $N_f = 10^4$ cycles, where the plastic strain range is given by $\Delta\varepsilon_p$ (at 10^4 cycles) = 0.0069 - 0.525 $\Delta\varepsilon_e$ (at 10^4 cycles), where the elastic strain-range line at $N_f = 10^4$ cycles; ($\Delta\varepsilon_e$ at 10^4) is shown as $\Delta\varepsilon^*_e$ in Fig. 41.

Point P_1 depends on fracture stress, which is not readily available in literature. However, fracture stress (which is the load at fracture divided by the area as measured after fracture) can be estimated by means of the following approximate relationship among fracture stress, ultimate tensile stress, and fracture ductility, thus,

$$\sigma_f = \text{UTS}(1 + D) \qquad \textbf{(Eq 34)}$$

This relation follows from Fig. 42, where each point is fixed by the data for one material.

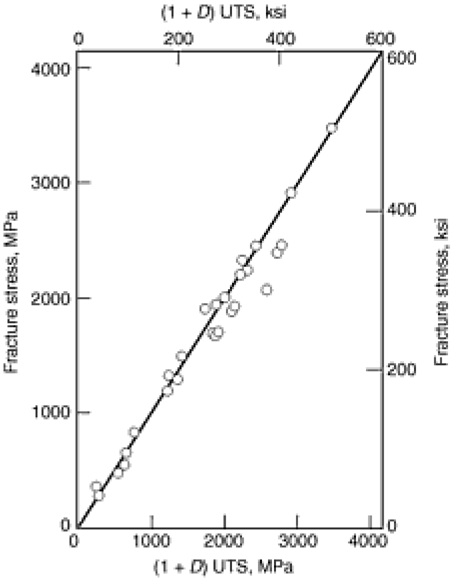


Fig. 42 Fracture stress versus tensile ductility

On the basis of the approximate equality in Eq 34, Manson noted that when E is known, only two tensile properties--ultimate tensile strength (UTS) and the reduction in area (to give D)--are needed to position the lines in Fig. 41 and thus obtain a prediction of fatigue behavior. Figure 43 shows a convenient graphical solution by Manson for locating the four points. For example, if UTS/E is 0.01 and the reduction in area is 50% (D = 0.694), the value of P_2 from the right-hand scale is 0.009 and that of P_3 from the top scale is 0.18. Locating the point with the coordinates UTS/E = 0.01 and reduction in area equal to 50% gives values for P_1 and P_4 of 0.042 and 0.0009, respectively. These points will locate the two strain-range lines, and the total strain-range curve can then be positioned to relate $\Delta\varepsilon$ and N_f for the material in question.

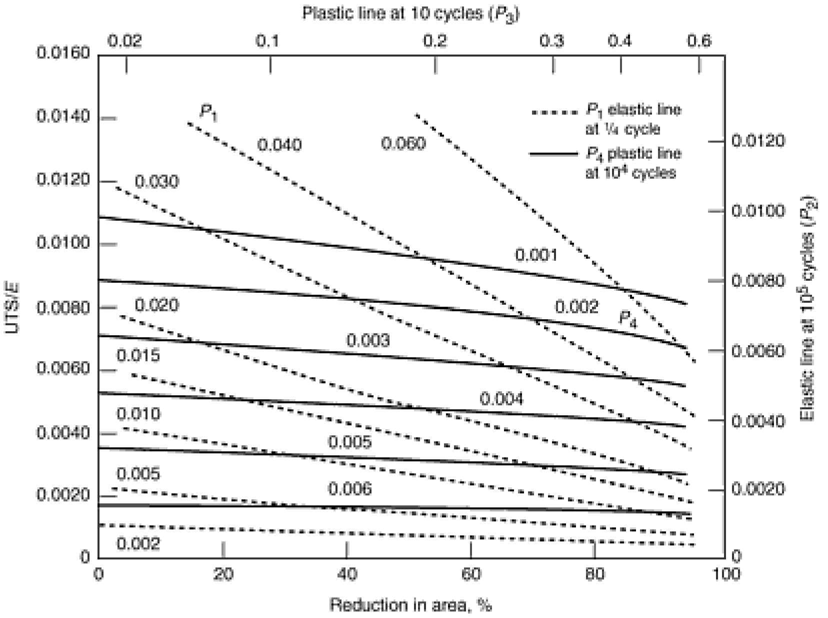
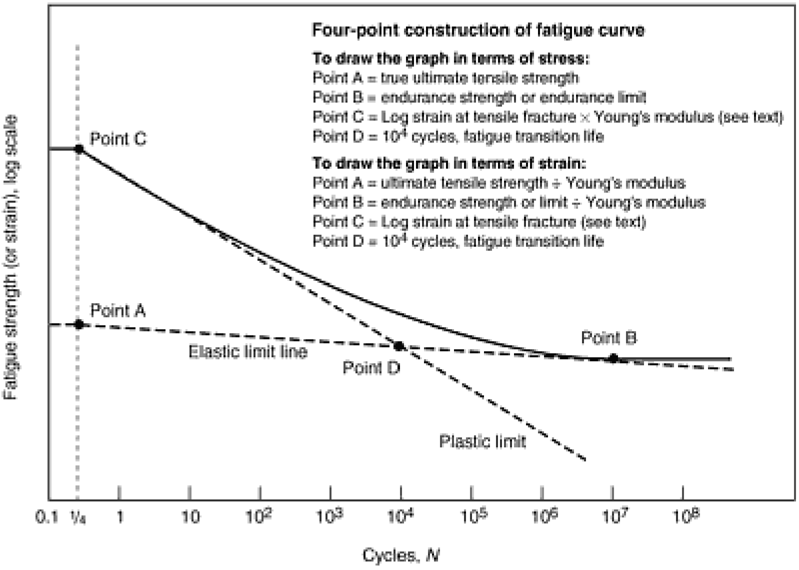


Fig. 43 Graphical solution to obtain the four points (P_1, P_2, P_3, and P_4, in Fig. 41) to position the elastic and plastic strain-range lines.

Stress-Based Four-Point Method. The four-point also applies to the construction of a stress-based *S-N* fatigue curve, as shown in Fig. 44. The four points A, B, C, and D in Fig. 44 can be defined in terms of either stress or strain. In terms of strain, the points are identical to points P_1, P_2, P_3, and P_4 in Fig. 41. For construction of an *S-N* fatigue curve, the points are determined as described below.



Four-point construction of fatigue curve

To draw the graph in terms of stress:
Point A = true ultimate tensile strength
Point B = endurance strength or endurance limit
Point C = Log strain at tensile fracture × Young's modulus (see text)
Point D = 10^4 cycles, fatigue transition life

To draw the graph in terms of strain:
Point A = ultimate tensile strength ÷ Young's modulus
Point B = endurance strength or limit ÷ Young's modulus
Point C = Log strain at tensile fracture (see text)
Point D = 10^4 cycles, fatigue transition life

Fig. 44 Schematic summary of four-point method for estimating fatigue strength or strain life

Point A (in terms of stress) is simply the ultimate tensile strength of the metal, plotted on the vertical axis of the graph at $N = \frac{1}{4}$. As in the strain-based approach, this assumes that the simple tensile test represents one-fourth of a single, completely reversed fatigue cycle--the peak positive value of the applied stress.

Point B, the right-hand locator of the elastic curve, is defined as the fatigue-endurance limit, if the metal has one; otherwise, point B is the endurance strength. Some ferrous alloys have an endurance limit, that is, a stress level below which fatigue failure will never occur, regardless of number of cycles. This is generally around 10^7 or 10^6 cycles, at which point the fatigue curve approaches zero-slope, or a horizontal line.

Many metals, particularly those that do not work harden, have no detectable endurance limit. Their long-life fatigue curves never become truly horizontal. For these metals, a pseudo-endurance limit, called endurance strength, is reported. Usually, this value is defined as the failure stress at some large number of cycles, for example, 10^7 to 10^{10}.

Point B can also be obtained from tensile-test data--a virtue of this technique, as handbook values for fatigue-endurance strengths or limits are often not available. Figure 45 is used to find the fatigue-endurance value from yield strength and true ultimate tensile strength for the material. The "ductility parameter" is simply calculated from handbook tensile data using the equation on the horizontal axis of the graph. Then find the "endurance-to-yield" strength ratio for the appropriate material. Multiply this ratio by "yield strength" to find the endurance value, which is point B.

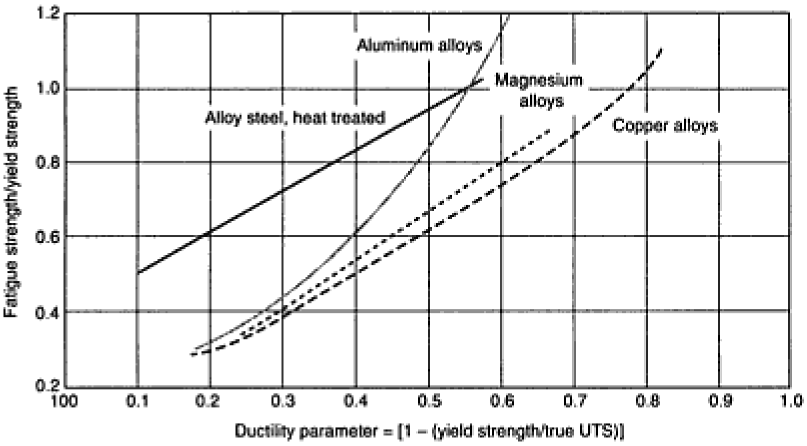


Fig. 45 Plot for estimating fatigue-endurance limits (point B in Fig. 44) for common structural alloy groups

Beyond point B, the ratio of ultimate tensile strength to yield strength can be used to approximate the slopes of the long-life portion of the fatigue curve. According to many researchers, a ratio greater than 1.2 suggests that the material strain hardens sufficiently to produce a pronounced endurance limit value, and the curve assumes a zero slope. For ratios less than 1.2, however, the curve will continue to drop beyond point B. The lower the ratio below 1.2, the further the fatigue curve deviates from a horizontal, zero-slope line beyond point B.

Because both endurance strength and endurance limit are reported in terms of stress, this value must be divided by Young's modulus for the metal if the fatigue curve is being constructed in terms of strain.

Point C is a value known as "fracture ductility." If natural, or true, strain at fracture for a simple tension test is known (which would be the distance between gage points at fracture divided by initial gage length), fracture ductility is the natural log of this value.

In most cases, however, reduction of area for a simple tensile test is given in handbooks. As before in the discussion on the universal slopes method, fracture ductility, ε_f, is estimated.

$$\varepsilon_f = \ln \frac{100}{100 - \text{RA}} \qquad \textbf{(Eq 35)}$$

where RA is percentage reduction of area.

Because fracture ductility is in units of strain, this value must be multiplied by Young's modulus to obtain point C in terms of stress. In all cases, point C is also plotted at $N = \frac{1}{4}$.

Point D is defined as the intersection of the plastic and elastic curves at 10^4 cycles. (According to the theory of "universal slopes," elastic and plastic strain curves intersect at $N = 10^4$). Thus, locate point D on the elastic curve and draw the plastic curve between points C and D. Now the fatigue curve can be drawn as the arithmetic summation of the elastic and plastic lines.

Comparison with Data for Steel, Aluminum, and Copper Alloys. To demonstrate the validity of the method described here, actual fatigue test results for various steel, aluminum, and copper alloys were compared with curves approximated from handbook data (P. Weihsmann, *Mater. Eng.,* March 1980, p 53). In addition, a more recent analysis by J.H. Ong (*Int. J. Fatigue,* Vol 15, 1993, p 13-19) on 49 steels demonstrates that the predicted values by the four-point correlation method and the universal slopes method give satisfactory agreement with experimental data. The analysis by Ong shows that the four-point method gives the best estimates for predicting fatigue properties from uniaxial tension tests.

Of the six comparisons shown (Fig. 46), fatigue data for steels and aluminum were taken from published sources. The measurements for copper fatigue are original, taken from tests on simulated squirrel-cage rotor, bar-to-end ring joints for induction motors.

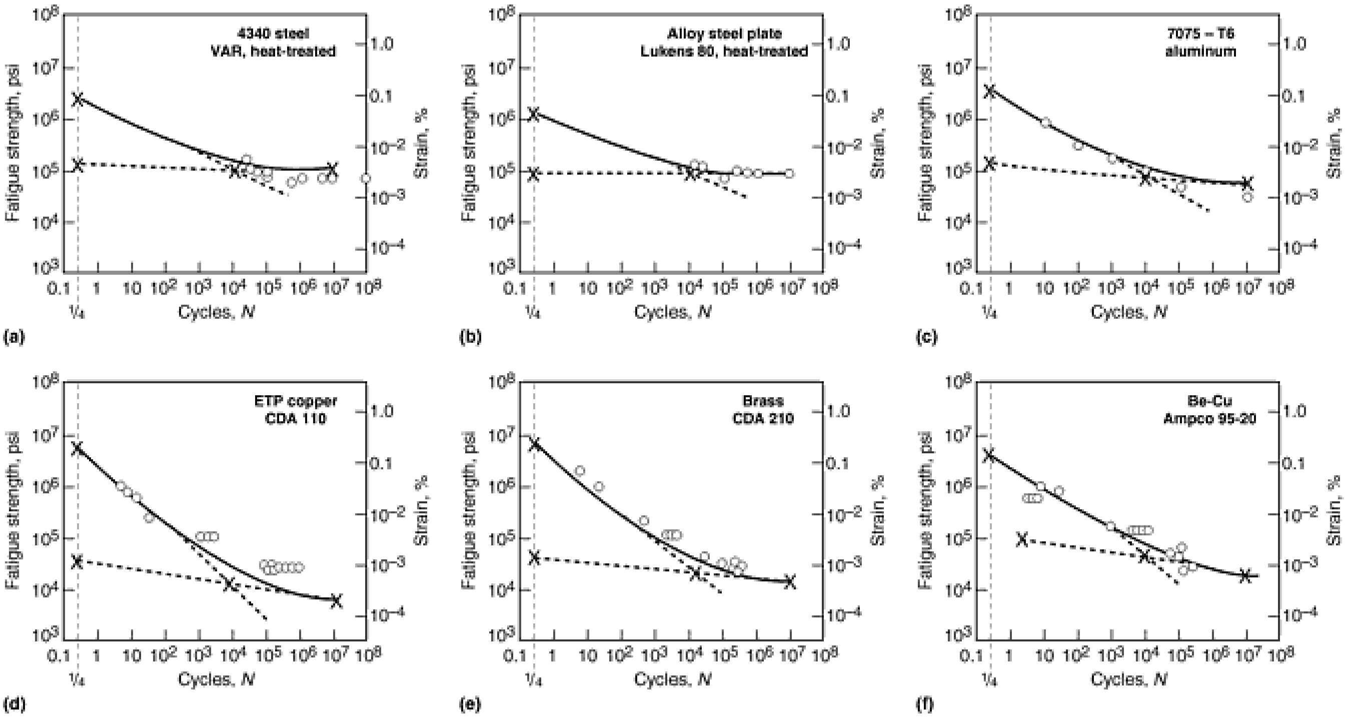


Fig. 46 Comparison of actual fatigue test results (open circles) with fatigue curves constructed by the four-point method from tensile data. Total fatigue life is a solid line and elastic and plastic components are dashed lines constructed from tensile data point (shown by Xs). (a) 4340 steel. (b) Alloy steel plate (Lukens 80). (c) 7075-T6 aluminum. (d) Electrolytic-tough-pitch (ETP) copper. (e) Brass. (f) Beryllium-copper alloy

Because these parts had been brazed prior to testing, the copper fatigue test data were assumed to represent essentially annealed material. Traceability of the data is not "ideal" in these cases, as handbook tensile data for the approximated curves were selected for truly annealed materials. Nevertheless, correlation between fatigue test data and the curves drawn from annealed tensile data is quite good, indicating that this technique appears to be perfectly acceptable for copper alloys as well.

Figures 46(a) to (f) were prepared from actual fatigue-test data (open circles) and from handbook tensile data (Xs). Fatigue curves constructed according to the techniques outlined in this article are shown in solid curves. Elastic and plastic strain curves used in the construction of the fatigue curves are dashed. While this is no substitute for thorough, conventional fatigue testing, reasonable correlation between the actual fatigue data and the simulated curves indicates that this technique can be a quick shortcut for approximating fatigue-life information.

Fatigue Crack Growth Testing

TESTING OF SMOOTH OR NOTCHED SPECIMENS generally characterizes the overall fatigue life of a specimen material. This type of testing, however, does not distinguish between fatigue crack initiation life and fatigue crack propagation life. With this approach, pre-existing flaws or crack-like defects, which would reduce or eliminate the crack initiation portion of the fatigue life, cannot be adequately addressed. Therefore, testing and characterization of fatigue crack growth is used extensively to predict the rate at which subcritical cracks grow due to fatigue loading. For components that are subjected to cyclic loading, this capability is essential for life prediction, for recommending a definite accept/reject criterion during nondestructive inspection, and for calculating in-service inspection intervals for continued safe operation.

Fracture Mechanics in Fatigue

Linear elastic fracture mechanics is an analytical procedure that relates the magnitude and distribution of stress in the vicinity of a crack tip to the nominal stress applied to the structure; to the size, shape, and orientation of the crack or cracklike imperfection; and to the crack growth and fracture resistance of the material. The procedure is based on the analysis of stress-field equations, which show that the elastic stress field in the region of a crack tip can be described by a single parameter, K, called the stress-intensity factor. This same procedure is also used to characterize fatigue crack growth rates (da/dN) in terms of the cyclic stress-intensity range parameter (ΔK).

When a component or a specimen containing a crack is subjected to cyclic loading, the crack length (a) increases with the number of fatigue cycles, N, if the load amplitude (ΔP), load ratio (R), and cyclic frequency (ν) are held constant. The crack growth rate, da/dN, increases as the crack length increases during a given test. The da/dN is also higher at any given crack length for tests conducted at higher load amplitudes. Thus, the following functional relationship can be derived from these observations:

$$\left(\frac{da}{dN}\right)_{R\nu} = f(\Delta P, a)$$

where the function f is dependent on the geometry of the specimen, the crack length, the loading configuration, and the cyclic load range.

The general nature of fatigue-crack growth and its description using fracture mechanics can be briefly summarized by the example data shown in Fig. 47. This figure shows a logarithmic plot of the crack growth per cycle, da/dN, versus the stress-intensity-factor range, ΔK, corresponding to the load cycle applied to a specimen. The da/dN-versus-ΔK plot shown is from five specimens of ASTM A 533 B1 steel tested at 24 °C (75 °F). A plot of similar shape is expected with most structural alloys; the absolute values of da/dN and ΔK are dependent on the material. Results of fatigue-crack-growth-rate tests for nearly all metallic structural materials have shown that the da/dN-versus-ΔK curves have the following characteristics: a region at low values of da/dN and ΔK in which fatigue cracks grow extremely slowly or not at all below a lower limit of ΔK called the threshold of ΔK, ΔK_{th}; an intermediate region of power-law behavior described by the Paris equation:

$$\frac{da}{dN} = C(\Delta K)^n$$

where C and n are material constants; and an upper region of rapid, unstable crack growth with an upper limit of ΔK that corresponds either to K_{Ic} or to gross plastic deformation of the specimen.

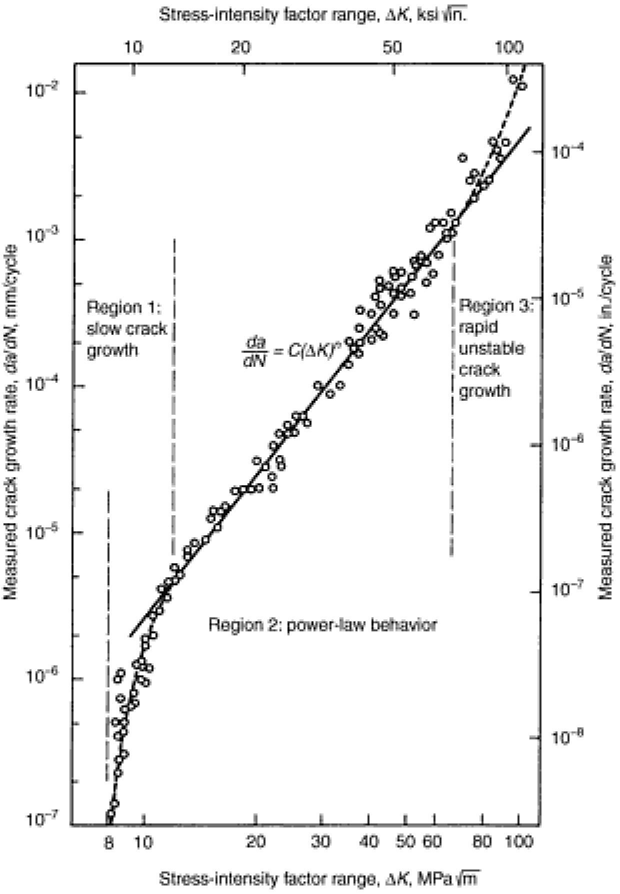


Fig. 47 Fatigue-crack-growth behavior of ASTM A 533 B1 steel with a yield strength of 470 MPa (70 ksi). Test conditions: R = 0.10; ambient room air; 24 °C (75 °F)

Test Methods

Testing procedures for measuring fatigue-crack-growth rates are described in ASTM method E 647. This method applies to medium-to-high crack-growth rates--that is, above 10^{-8} m/cycle (3.9×10^{-7} in./cycle). For applications involving fatigue lives of up to about 10^8 load cycles, the procedures of E 647 can be used. Fatigue lives greater than about 10^6 cycles correspond to growth rates below 10^{-8} m/cycle, and these require special testing procedures, which are related to the threshold of fatigue-crack growth shown in Fig. 47.

ASTM method E 647 describes the use of center-cracked specimens and compact specimens. The specimen thickness-to-width ratio, B/W, is smaller than the 0.5 value for K_{Ic} tests; the maximum B/W values for center-cracked and compact specimens are 0.125 and 0.25, respectively. With the thinner specimens, it is feasible to use crack-length measurements on the sides of the specimens as representations of through-thickness crack-growth behavior. The specimens are loaded in the same general manner as for K_{Ic} testing. For tension-tension fatigue loading, the K_{Ic} loading fixtures often can be used. For this type of loading, both the maximum and minimum loads are tensile, and the load ratio, $R = P_{min}/P_{max}$, is in the range $0 < R < 1$. A ratio of $R = 0.1$ is commonly used. Tension-compression loading can be performed with the compact specimen, but it is a more complex type of loading and requires more care.

Testing normally is performed in laboratory air at room temperature; however, any gaseous or liquid environment and temperature of interest may be used in order to determine the effect of corrosion or other chemical reaction on cyclic loading. Cyclic loading may involve various wave forms for constant-amplitude loading, spectrum loading, or random loading.

For constant-amplitude loading, a set of crack-length-versus-elapsed-cycle data (a versus N) is collected, with the specimen loading, P_{max} and P_{min}, generally held constant. The minimum crack length increment Δa, between data points is required by ASTM E 647 to be larger than a certain measurement of erroneous growth rates from a group of data points that are too closely spaced relative to the precision of data measurement and relative to the scatter of the data. The growth rates may be calculated by either of two methods. The secant method is simply the slope of the straight line connecting two adjacent data points. This method, although simpler, results in more scatter in measured crack-growth rate. The polynomial method fits a second-order polynomial expression (parabola) to typically 5 to 7 adjacent points, and the slope of this expression is the growth rate. The polynomial method, particularly when used with a large number of adjacent points, eliminates some of the scatter in growth rate, which is inherent in fatigue testing. The measured values of growth rate typically are plotted as in Fig. 47, where ΔK is calculated from $\Delta P = P_{max} - P_{min}$ (for tension-tension loading) using a K expression.

The measured growth-rate data are represented by an equation of the form of the Paris equation:

$$\frac{da}{dN} = C(\Delta K)^n$$

where the material constants C and n apply only within a certain range of da/dN and ΔK values. Other relationships based on the Paris equation, such as the commonly used Forman equation, are used to represent the variation of da/dN with other key variables, including load ratio, R, and the critical K value, K_c, at which fast fracture of the specimen occurs. The Forman equation is:

$$\frac{da}{dN} = \frac{C\,(\Delta K)^n}{(1 - R)\,K_c - \Delta K}$$

where C and n are material constants of the same types as those in the Paris equation, but of different values. An advantage of the Forman equation is that it describes the type of accelerate da/dN behavior that is often observed at high values of ΔK and is not described by the Paris equation. For example, for zero-to-tension loading (in which $R = P_{min}/P_{max} = 0$), as ΔK approaches K_c in the Forman equation, da/dN increases rapidly, and this is often observed in tests. In addition, the Forman equation describes the often-observed decrease in da/dN associated with an increase in R from zero toward one. So when it is necessary to describe the effect of ΔK approaching K_c, or the effect of R on da/dN, the Forman equation can be used to represent the da/dN behavior. When only ΔK, the primary variable affecting da/dN, is involved, the less complex Paris equation may be used.

Cyclic crack growth rate testing in the low-growth regime (region 1 in Fig. 47) complicates acquisition of valid and consistent data, because the crack growth behavior becomes more sensitive to the material, environment, and testing procedures in this regime. Within this regime, the fatigue mechanisms of the material that slow the crack growth rates are more significant (see the article "Fatigue Crack Threshold Behavior and Analysis" in *Fatigue and Fracture,* Volume 19, *ASM Handbook*).

It is extremely expensive to obtain a true definition of ΔK_{th}, and in some materials a true threshold may be nonexistent. Generally, designers are more interested in the fatigue crack growth rates in the near-threshold regime, such as the ΔK that corresponds to a fatigue crack growth rate of 10^{-8} to 10^{-10} m/cycle (3.9×10^{-7} to 10^{-9} in./cycle). Because the duration of the tests increases greatly for each additional decade of near-threshold data (10^{-8} to 10^{-9} to 10^{-10}, etc., m/cycle), the precise design requirements should be determined in advance of the test. Although the methods of conducting fatigue crack threshold testing may differ, ASTM E 647 addresses these requirements.

In all areas of crack growth rate testing, the resolution capability of the crack measuring technique should be known; however, this becomes considerably more important in the threshold regime. The smallest amount of crack length resolution as possible is desired, because the rate of decreasing applied loads (load shedding) is dependent on how easily the crack length can be measured. The minimum amount of change in crack growth that is measured should be ten times the crack length measurement precision. It is also recommended that for noncontinuous load shedding testing, where $(P_{max_1} - P_{max_2})/P_{max_1} > 0.02$, the reduction in the maximum load should not exceed 10% of the previous maximum load, and the minimum crack extension between load sheds should be at least 0.50 mm (0.02 in.).

In selecting a specimen, the resolution capability of the crack measuring device and the K-gradient (the rate at which K is increased or decreased) in the specimen should be known to ensure that the test can be conducted appropriately. If the measuring device is not sufficient, the threshold crack growth rate may not be achieved before the specimen is separated in two. To avoid such problems, a plot of the control of the stress intensity (*K* versus *a*) should be generated before selection of the specimen.

When a new crack-length measuring device is introduced, a new type of material is used, or any other factor is different from that used in previous testing, the *K*-decreasing portion of the test should be followed with a constant load amplitude (*K*-increasing) to provide a comparison between the two methods. Once a consistency is demonstrated, constant-load amplitude testing in the low crack growth rate regime is not necessary under similar conditions.

Creep, Stress-Rupture, and Stress-Relaxation Testing

THE FLOW or plastic deformation of a metal held for long periods of time at stresses below the normal short-time yield strength is known as creep. Although we normally think of creep as occurring only at elevated temperatures, room temperature can be high enough for creep to occur in some metals. In lead, for example, creep at room temperature is common. In many cases, lead pipes must be supported to prevent sagging under their own weight.

The development of steam turbines and jet engines has greatly increased interest in creep because, in these, the metal parts must withstand high loads at high temperatures for long times. The high centrifugal loads tend to cause certain parts to elongate or distort. Tolerances must be kept close to be efficient; yet if the metal parts deform too much, this spacing will be eliminated and failure will occur. In most cases, the parts cannot be made sufficiently heavy to prevent all creep because the weight penalty would reduce efficiency too much. Many such parts are therefore designed for a certain expected life span. For this, accurate data are needed to determine how much the metal part can be expected to deform under the conditions of stress and temperature to be encountered in service. Tests that measure the deformation of a metal as a function of time at constant load and temperature are known as creep tests.

Creep Phenomena

A typical creep curve is shown in Fig. 48. The vertical (*y*) axis is creep strain and the horizontal (*x*) axis is time plotted on logarithmic coordinate. The curve consists of three parts: primary, secondary, and tertiary creep, or first-, second-, and third-stage creep. The strain shown is plastic or permanent strain. When a creep specimen is loaded, there will be some elastic extension of the specimen, but this is not shown in this curve. In the primary stage, the initial creep rate shows a continuous decrease with time. In second-stage creep, the creep rate is considered essentially constant. In the third stage, the strain rate increases rapidly to fracture. This increase in the third stage is due, in part, to the reduction in cross-sectional area and thus the increasing true stress. Measurements made of specimen cross section during third-stage creep indicate that the increase in strain rate is not due only to necking or reduction in cross-sectional area, however.

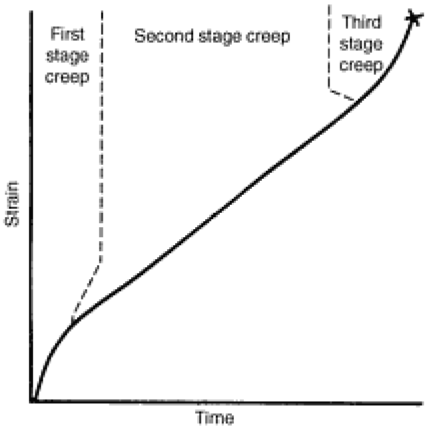


Fig. 48 Idealized creep curve

Although, in the idealized creep curve shown in Fig. 48, the creep rate is shown as constant in the second stage, this does not occur in practice. If the test is long enough to show all stages of creep, the curve will show a continually diminishing rate of creep to a point where the curve inverts and the creep rate starts to increase again (Fig. 49). The change in rate may be very slight over time; in some cases, the curve may approach a straight line.

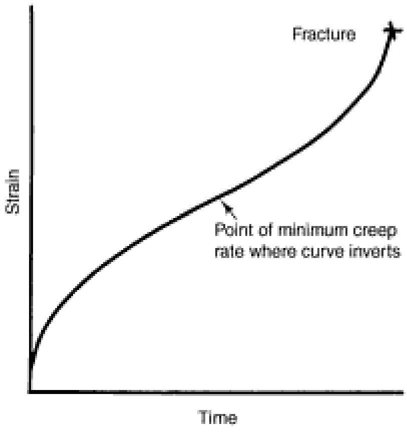


Fig. 49 Creep curve with minimum creep rate and point of inversion

Rupture Tests

The rupture test is valuable in determining tendencies of materials that may have to break under an overload. It finds much use in selection of materials for applications where dimensioned tolerances are not critical but rupture could not be tolerated. The rupture test is similar to a creep test except that no strain measurements are made during the test. The specimen is stressed under a constant load at constant temperature as in the creep test, and the time for fracture to occur is measured. Measurements are also made of the elongation and reduction in area of the broken specimen. Stresses are higher than those used for creep tests. An example of a typical application of the rupture test would be for testing boiler pipes. This test is also called the stress-rupture test, or time-to-rupture test.

Relaxation Tests

The relaxation test is somewhat similar to the creep test, but the load continually decreases instead of remaining constant. This test is primarily of value in evaluating bolt materials. When a bolt is drawn up tight, a tensile load is present in the bolt and the bolt is elongated slightly. This causes a clamping load on whatever the bolt is mounted on. If the bolt creeps (extends or relaxes), this clamping load will be reduced. If the bolt elongates sufficiently to remove all tension, it no longer fulfills its function. In a relaxation test, the load is reduced at intervals in order to maintain a constant elongation (strain). A relaxation curve thus takes the general shape shown in Fig. 50. Note that the *y*-axis in this curve is stress or load rather than strain (elongation) as in the creep curve.

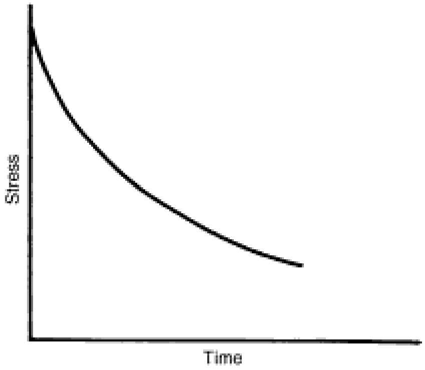


Fig. 50 Relaxation curve

Typical Procedure for Making a Creep Test

Selection and Preparation of Specimen. The same precautions used in selecting and preparing a specimen for a short-time tension test apply to specimens for creep testing. The specimen should be selected to be truly representative of that which it is supposed to represent. Machining and grinding should follow procedures to produce a surface as nearly stress-free as possible. There should be no undercutting at the fillets, and the gage length should be uniform in cross section or very slightly smaller at the center of the gage length.

The specimen is carefully identified in as much detail as is appropriate--type of metal, heat number, vendor, etc.--and this information is recorded with the specimen's measurements. Sometimes gage marks, for measuring total extension, are made on the specimen. Such marks or scribe lines must be used with care, because the depressions or scribe lines can cause premature failure on some materials. Any operation, such as stamping the ends of the specimen, must be used with care to avoid any damage to the specimen.

Loading. In mounting the specimen in the adapters and load train, care is needed to avoid straining of the specimen in handling. Strain can occur when threading the specimen into the adapters and when handling the load train with the specimen in place, especially if the specimen is very small or brittle. The load train (specimen adapters or grips, pull rods, etc.) with the specimen in place should be carefully examined for any misalignment that will cause bending of the specimen under load. The upper load train should be suspended from the lever arm and the compensating weight adjusted so that the lever arm balances. The strain-measuring clamps and extensometer or the platinum strips are attached to the specimen, and the load train is inserted into the furnace with the specimen centered. The specimen must be stabilized at temperature before being loaded, Also, the extensometer should be adjusted and zeroed.

Loading of the weight pan should be done smoothly and without excessive shock. If the specimen is to be step loaded, the weight is placed on the weight pan in measured increments and the strain corresponding to each step of loading is recorded. The loading curve thus obtained is used in determining the elastic modulus. If step loading is not used, a method of applying the load smoothly must be used. Smooth application can be done by having a support such as a scissors jack under the load pan during loading. When all weights are in place, the supporting jack is smoothly lowered from under the weight pan.

Data Collection. Reading of strain should be made frequently enough to define the curve well. This diligence will necessitate much more frequent readings during the early part of the test than later. The elastic portion of the stress-strain curve can be obtained by measurement of the instantaneous contraction when the load is removed at the end of the test if the specimen has not broken.

Temperature Control. In bringing the specimen to temperature, it is important that the specimen not be overtemperatured. A common practice is to bring the specimen up to about 30 °C (50 °F) below the desired temperature in about 1 to 4 h, and then take considerably longer in bringing the specimen to the desired temperature and adjusting for good stabilization. It should be understood that a period of time above the desired temperature is not cancelled in effect by an equal period at a temperature the same amount below the desired temperature. Any rise in temperature above the desired temperature of more than a small amount (such as defined by ASTM Recommended Practice for Conducting Creep and Time for Rupture Tension Tests of Materials) should be rejected. The limits specified in this recommendation are ±1.7 °C (±3 °F) up to 980 °C (1800 °F) and ±2.8 °C (±5 °F) above 980 °C (1800 °F). At temperatures very much above 1095 °C (2000 °F), the limits are broadened somewhat. Variation of temperature along the specimen from the nominal test temperature should vary no more than these limits at these temperatures. These limits refer to indicated variations in temperature according to the temperature recorder.

Every effort should be made to ensure that the indicated temperature is as close to true temperature as possible. There is the possibility of both thermocouple error and instrument error. Thermocouples, especially base-metal thermocouples, drift in calibration with use or because of contamination. Other possible errors can result from incorrect lead wires or incorrect connection of lead wires, direct radiation on the thermocouple bead, or other causes. Representative thermocouples should be calibrated from each lot of wires used for base-metal thermocouples, and, except at low temperatures, base-metal thermocouples should not be re-used without slipping back to remove the wire exposed to high temperatures and rewelding. Noble-metal couples are generally more stable. However, they are also subject to error due to contamination and need to be annealed periodically. Annealing can be done by connecting a variable transformer to the two wires and sending enough current through the wire to make it incandescent.

When the thermocouple is attached to the specimen, the junction must be kept in intimate contact with the specimen. The bead at the junction should be as small as possible, and there must be no twisting of the thermocouple elsewhere that could cause shorting. Any other metal contact across the two wires will cause shorting and erroneous readings. Many authorities recommend shielding the thermocouple junction from radiant heating.

Temperature-measuring, controlling, and recording instruments must be calibrated periodically against some standard. The calibration is usually done by connecting a precision potentiometer to the thermocouple terminals on the instrument and feeding in millivoltages corresponding to the output of the thermocouple at each of several temperatures. Tables of millivolt output for various types of thermocouples are readily available from manufacturers of precision potentiometers. Most creep and rupture machines are equipped with a switch that automatically shuts off the timer when the specimen breaks. In creep tests, the load is usually selected low enough so that rupture does not occur. The microswitch that shuts off the timer also shuts off or lowers the temperature of the furnace on many other creep-rupture units. In some furnaces, the life of the heating element is severely reduced if the furnace is shut off after each test; so for some furnaces the temperature is lowered to some lower control temperature, such as 540 or 650 °C (1000 or 1200 °F).

Interrupted Tests. Sometimes, because of a power failure or other problem, it becomes necessary to interrupt a test, for instance, the specimen is cooled, then reheated. For many materials, this change appears to have little effect on either creep properties or time to rupture if the times of cooling and heating are not very great. It cannot be stated, however, that such treatment will not affect any materials. Any interruption of a test should be reported.

Presentation of Data

Creep. The usual method for presenting creep data is in the form of a curve showing percent creep strain as the vertical axis and time as the horizontal axis. Time is usually plotted on a log scale to show the early part of the curve in good detail and yet prevent the curve from being excessively long. Sometimes a whole family of curves is plotted on the same coordinates to show the effect of different temperatures or different stresses on one material.

Other methods for plotting data include time to reach a given percent of creep versus load at a constant temperature or time to reach a given percent of creep versus temperature at constant load.

The loading curve, showing the strain versus load as the specimen is loaded, is plotted separately and is used in computing the elastic modulus of the material at temperature.

Rupture. Rupture data are presented in several types of graphs. One type has stress as the vertical axis versus log of time-to-rupture (at constant temperature) on the horizontal axis. Usually, stress-rupture data are presented by means of a parameter plot. Stress is plotted against a parameter value that relates to both time and temperature. Several different parameters have been used. A widely used one, the Larson-Miller parameter, follows the formula $P = (T + 460)(\log t + c)$.This means that the parameter value P equals the Rankine temperature (460 + the temperature, T, in degrees Fahrenheit) times the log (base 10) of the time, t, in hours plus a constant c. The constant (c) has various values depending on the material but usually runs from about 17 to 23 for most materials tested. The value of c is determined by plotting log of time versus $1/[T(°F) + 460]$ using rupture data from several tests at constant stress but different temperatures on the same material. This produces a series of straight lines convering as on a single point. At this point $\log t = c$, and this constant is theoretically the best constant to use for the data involved.

Shear Testing

IN GENERAL, the amount of existing shear-strength data is seriously less than the published data available for other mechanical properties. Stores of data that deal with mechanical properties, such as tensile and yield strength, hardness, and ductility for virtually all metals and metal alloys, and in a wide variety of conditions, are readily obtainable.

At least two reasons can be identified to explain the scarcity of shear-strength data. First, the demand is low, because the number of components that are loaded in shear under service conditions is far less than that of components loaded in tension, compression, bending, or torsion. Probably the primary reason for the lack of published data on shear strength is the difficulty in obtaining accurate test data. Shear testing inherently involves a number of variables; thus, the tests are less reproducible than testing for properties, such as tensile or yield strength. Therefore, most shear testing has been performed by means of nonstandard equipment and procedures operating on arbitrary bases, thus producing results that are empirical.

The greatest needs for shear-test data are in the designing of structures that are riveted, pinned, or bolted together and where service stresses are actually in shear. Notable examples of such structures are found in the aerospace industry. The required standardization is given by ASTM B 565.

Single- and Double-Shear Testing

In the many tests that have been devised for evaluating shear strength, both single- and double-shear testing have been used. The double-shear technique is far more accurate, however, making those results more reproducible than results for the single-shear technique.

Compression-type loading for a shear fixture is shown in Fig. 51, with a specimen being tested in double shear. This type of fixture may also be used for single-shear tests.

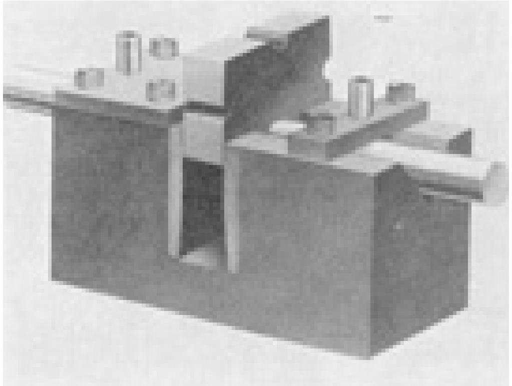


Fig. 51 Shear test fixture of the compression loading type used for single or double shear test. Courtesy Tinius Olsen Testing Machine Company

Procedure. The test specimen is assembled in the fixtures, per ASTM B 565, and loaded in tension until complete failure occurs. Crosshead speed during the test should not exceed 19.1 mm/min (0.750 in./min), and loading rate should not exceed 690 MPa/min (100 ksi/min). The maximum load in double shear is determined by the direct reading on the testing machine.

Calculation of Shear Stress

The calculation of stress in double shear is a simple mater of dividing the machine load by the area of the cross section ($\pi D^2/4$). It follows, then, that single-shear stress is one-half of this value, or:

$$\text{Single-shear stress} = \frac{P/2}{\pi D^2/4}$$

where P is load in kilograms (pounds), and D is diameter in millimeters (inches).

As previously stated, shear testing is more vulnerable to the effects of variables than certain other mechanical tests, such as tests for tensile or yield strength. Even when the fixtures and test specimens meet specified tolerances, some variations are bound to exist in the test-jig assembly that will be reflected as variables in the results.

The presence or absence of lubricant on the surfaces of the specimens and test fixtures can be responsible for substantial variations in the results. For example, a lubricated specimen may cause a reduction in shear strength of as much as 3%.

To minimize this variable, it is recommended that the test fixtures and specimens be carefully cleaned prior to testing, preferably by means of ultrasonic cleaning in a suitable solvent.

Torsion Testing

IN THE TORSION TEST, a specimen is subjected to twisting or torsional loads to simulate service stresses for such parts as axles, crankshafts, twist drills, and spring wire. The test has not been standardized and is rarely specified. However, the torsion test provides information such as modulus of elasticity in shear (sometimes called modulus of rigidity), the shearing yield strength, and the modulus of rupture (apparent ultimate shear strength). The torsion test may also be performed as a high-temperature twist test on materials such as tool steels to determine forgeability. The test does not provide meaningful results for very brittle materials such as cast irons, because these materials would fail in diagonal tension before the shear-strength limit was reached.

General Procedure

In torsion testing, the specimen is clamped in clamping heads so that the specimen remains as straight as possible during testing. The test specimen is then twisted at a slow, uniform rate until it breaks, or until a specified number of turns is obtained. The number of turns is recorded. If the number of turns falls within an acceptable range, the test specimen is considered to have passed the test. Results of the torsion test are largely comparative and have no standardized values.

Torsion testing is frequently employed to assess the quality of brazed joints for sheet-metal products. A T-joint of sufficient length is brazed and then subjected to two full turns in torsion. Visual examination is made to determine if failure has occurred in the brazed joint.

One of the only standardized applications of the torsion test applies to torsion testing of wire (ASTM E 558).

An example of a torsion-testing machine is presented in Fig. 52.

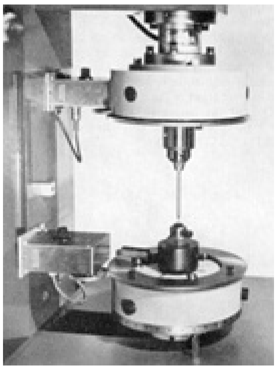


Fig. 52 Close-up of a 10,000 in. · lb (1100 N · m) torsion-testing machine with special tooling for Phillips screwdriver bits. Courtesy of Tinius Olsen Testing Machine Company

Data

Torsion data are usually presented as torque-twist curves, in which the applied torque is plotted against the angle of twist. Torsion produces a state of stress known as pure shear, and the shear stress at yielding can be calculated from the torque at yielding and the specimen dimensions. The maximum stress for a cylindrical specimen (at the surface) can be calculated from the following relation:

$$S = \frac{16T}{\pi d^3}$$

where S is maximum shear stress in MPa (ksi), T is torque in N · m (lb · in.), and d is specimen diameter in cm (in.). This formula holds only when the strain is proportional to stress, but it is commonly used for computing higher stresses and for determining modulus of rupture (apparent ultimate shear strength).

The total torsional deformation is measured as angular twist of one end of the gage length in relation to the other. In order to obtain the angular twist per inch of gage length, the total angular twist is divided by the gage length. The angular twist per inch of gage length can then be converted into shear strain, in inches per inch, by multiplying by half the diameter of the specimen.

E_s, the modulus of elasticity in shear (sometimes called the modulus of rigidity), can be calculated from the following formula:

$$E_s = \frac{SL}{r\theta}$$

where S is maximum shear stress, in MPa (ksi); L is the gage length of the specimen, in cm (in.); r is the distance from the axis of the specimen to the outermost fiber (half the diameter), in cm (in.); and θ is the angle of twist, expressed in radians, in length L.

The yield strength is generally defined as the maximum stress developed by a torque producing an offset of 0.2% from the original modulus line, analogous to the method used for determining tensile yield strength.

Comparison of Torsional and Tension Data

From the torque-twist diagram it is simple to obtain a shear stress-shear strain diagram. The great advantage of the torsion test over the tension test is that large values of strain can be obtained without complications such as necking. One problem of torsional tests is that the stress is not constant throughout the cross section. This problem can be circumvented by using tubular specimens. If the results of a tension test and a torsion test are plotted for the same low-carbon steel, the two curves will be markedly different. However, if the two curves are normalized by converting the normal stress and longitudinal strain in the uniaxial test and the shear stress and strain in the torsion test into effective stress and strain, the two curves come into close correspondence. The effective streses and strains are determined by well-known equations (for instance, Eq. 1.67 and 1.81 in *Mechanical Metallurgy: Principles and Applications,* by M.A. Meyers and K.K. Chawla, Prentice-Hall, 1984). These results show that the work hardening of the material is a function of the amount of plastic strain and does not depend on the state of stress. Such is not the case for all materials, however. Differences in texture due to different constraints can be responsible for substantial differences in the effective stress-strain curve.

Formability Testing

FORMABILITY is the technical term used to describe the ease with which a metal can be shaped through plastic deformation. Usually, it is synonymous with the term "workability." The evaluation of the formability of a metal involves both measurement of resistance to deformation (strength) and determination of the extent of plastic deformation that is possible before fracture (ductility). The emphasis in most formability tests, however, is on the amount of deformation required to cause fracture.

Because of the diverse geometries of the tools and workpieces and the various ways that forces of deformation are applied, different metalworking processes produce varying stress states. These can be divided into two broad categories: bulk-deformation processes, such as forging, extrusion, and rolling, where the stress state is three-dimensional, and sheet-forming processes, such as deep drawing and stretch forming, where the stress state is two-dimensional and lies in the plane of the sheet. The tests that simulate bulk-formability testing are given in the section "Compression Testing" in this article.

Bend Tests

Bend tests are among the most frequently used tests for evaluating the ductility of a metal or welded joint by measuring its ability to resist cracking during bending. Bending is the process by which a straight length is transformed into a curved length. The fibers of the metal on the outer (convex) surface of the bend are stretched, thus inducing tensile stresses. Simultaneously, the fibers on the inner (concave) surface of the bend are placed in compression. ASTM methods E 190, E 290, and E 855 provide descriptions of the various procedures.

General Methods

Bend Radius. For a given bending operation, the bend radius, *R*, cannot be made smaller than a certain value, or the metal cracks on the outer (tensile) surface. Usually, this minimum bend radius ($R_{\min}$) is expressed in terms of multiples of the specimen thickness, *t*. Thus, a material with a 3*t* minimum bend radius can be bent without cracking through a radius equal to three times the specimen thickness. It follows, then, that a material with a minimum bend radius of 1*t* has greater formability; whereas a minimum bend radius of 5*t* indicates a less formable material.

Test Specimens. Bend-test specimens are usually in the form of a rectangular beam. Wherever possible, as with a plate or a sheet, the full thickness of the material should be used. Generally, the specimen thickness should not exceed 40 mm ($1\frac{1}{2}$ in.). When using a machined specimen of reduced thickness, the as-fabricated surface should be retained as a surface of the bend specimen. This surface should be oriented in the bend fixture as the tensile surface. For specimens cut from plate material, the width should be twice the thickness, but no less than 20 mm ($\frac{3}{4}$ in.). For thin specimens cut from sheet, the width should exceed eight times the thickness. The ratio of width to thickness affects the stress state produced in bending and, therefore, the ductility measured in the test. For this reason, bend-test results made on thin sheet should not be compared with those obtained with thicker plate to avoid erroneous conclusions about the formability of the materials.

The length of a bend-test specimen must be of some minimum that varies with thickness. Length, however, is not critical if the specimen is long enough to accomplish the bending operation. The edges of the specimen may be rounded to a radius not to exceed 1.6 mm ($\frac{1}{16}$ in.) to minimize edge cracking. Flame-cut surfaces should be machined to remove heat-affected metal. Sheared edges should be machined or smoothed on an abrasive belt to remove the sheared edge. Although bend testing usually is performed with specimens of rectangular cross section, round specimens may also be used.

Bend specimens may be cut from sheet or plate to evaluate the basic formability of the material or test the formability of an as-fabricated surface. Because most fabricated products have mechanical properties that are directional (anisotropic), directionality is an important consideration in making the test. Figure 53 shows the orientation of the bend-test specimen with the rolling direction for a longitudinal orientation and a transverse orientation. The transverse orientation generally shows lower ductility, because the tensile bending stresses are oriented perpendicular to the fiber structure developed by the rolling deformation.

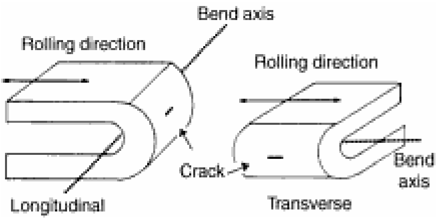


Fig. 53 Relative orientations of specimens for longitudinal and transverse bend tests. Arrows indicate direction of rolling. Source: Semi-Guided Bend Test for Ductility of Metallic Materials, ASTM E 290-80

The quality of welds often is evaluated by bend testing (ASTM E 190). A specimen is cut from the welded assembly with the weld in the center of the specimen. The weld may be either transverse or parallel to the length of the specimen.

Free Bend Tests

A free bend test is one in which the curvature of the bend is left "free" to take its natural shape. As shown in Fig. 54, the specimen is given a preliminary bend in a bending fixture (Fig. 54a) and then is transferred to a free bend fixture (Fig. 54b) where the bend is completed.

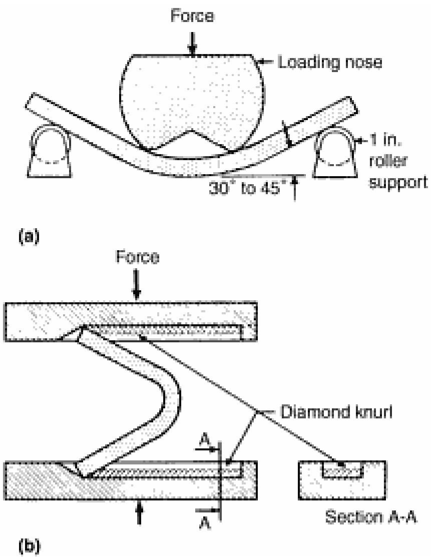


Fig. 54 Free bend tests. (a) A partial bend is made with the specimen in a horizontal position. (b) The specimen is positioned vertically, and the two knurled jaws are forced together until the specimen fractures or makes a 180° U-bend.

For moderately ductile materials, the formability is evaluated by the bend angle (α) that can be achieved before cracking occurs on the tensile face (outside surface) of the bend. For a highly ductile material that can be bent flat on itself (α = 80°), the ductility is evaluated on the thickest specimen for which this can be done without cracking.

Restricted (Controlled) Bend Tests

A restricted bend test is one in which the test specimen is made to bend closely around a predetermined radius, *R*. Various examples of this test are shown in Fig. 55. The test shown in Fig. 55(a) usually is called a guided-bend test. The need for a test fixture sometimes may be eliminated by using a soft metal support to accommodate the punch, as in Fig. 55(b). For thin sheet metal, the bending force may be applied by a hand-operated lever, or alternatively, the sheet may be hammered over the bending die with a plastic or rawhide mallet (Fig. 55c). ASTM E 290 describes this test in detail.

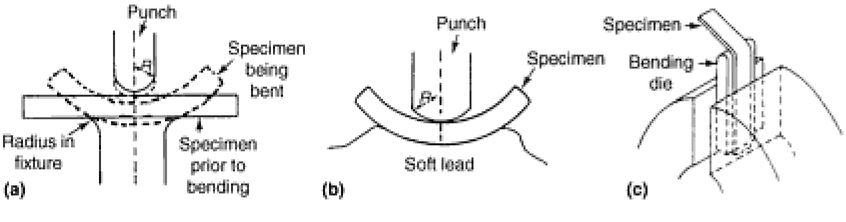


Fig. 55 Restricted bend tests. (a) Guided bend test wherein the test material is forced through a fixture of predetermined radius. (b) Modification of guided bend test using soft metal for the fixture. (c) Method of clamping the specimen while bending it over a predetermined radius

Ordinarily, a grid pattern is lightly scribed on the tensile surface of the bend specimen before the restricted bend test. This surface is observed during the test, either with a mirror or by bending in small increments, to determine when the cracks first appear. At this point, the angle of bend is recorded, or the elongation of the tensile surface is determined from the grid network. Alternatively, the minimum bend radius that will permit bending through a fixed bend angle is determined as the measure of formability.

Bend Tests on Very Ductile Materials

Bend tests on very ductile materials are less controlled than those discussed earlier, but they are more severe tests. For a sheet, the basic test is to determine whether the sheet can be bent flat on itself through 180° without cracking. A further test of ductility is to cross fold the sheet once again across the first fold (Fig. 56a). Bend tests are made on tubes by first flattening the tube, as shown in Fig. 56(b). This applies two separate transverse bends of nearly 180°. Subsequently, the flattened tube can be folded along its longitudinal axis (Fig. 56c).

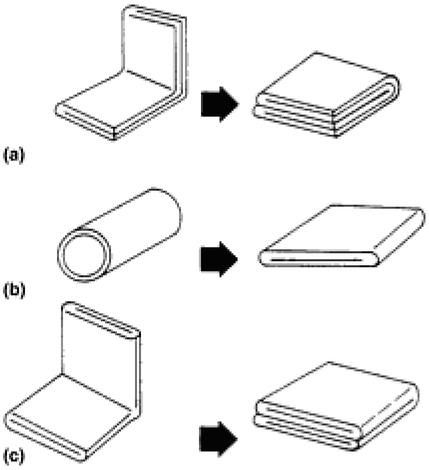


Fig. 56 Fold tests on ductile sheet or tube (see text)

Sheet-Formability Tests

Several tests have been developed to evaluate the formability of sheet metal, Most complex sheet-forming operations can be resolved into a combination of bending plus stretching and drawing. In a pure stretch-forming operation, the edges of the blank strip are clamped, and the shape is produced by multidirectional stretching over the contours of the deforming tool or punch. Sheet-metal drawing, usually called deep drawing, utilizes the radial drawing of the sheet-metal blank into the die under the action of the punch. In deep drawing, the outer portion of the blank shrinks in diameter under circumferential compression. To prevent the blank from buckling, the blankholder must exert sufficient pressure to prevent wrinkling but not enough pressure to restrict the sheet from drawing into the die. Thus, in deep drawing, no deformation occurs in the central region of the punch directly under the punch; whereas in stretch forming, the maximum deformation occurs in this region. Figure 57 shows the essential differences between stretching and drawing.

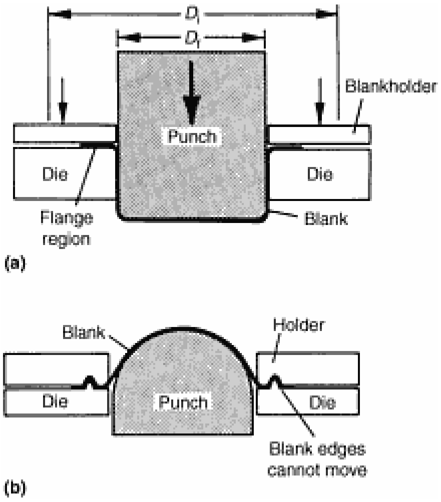


Fig. 57 Two operations that simulate stamping: (a) deep drawing and (b) stretching

The ability of the metal to undergo stretching is enhanced by a high value of strain hardening. Thus, a high value of strain-hardening exponent minimize failure in stretch forming. The ability to withstand deformation in deep drawing, without failure, derives from the crystallographic texture of the metal sheet produced during rolling. The desired texture is such that the slip systems are aligned to give higher strength in the thickness of the sheet than in the plane of the sheet. As the plastic-strain ratio, *r*, becomes greater, the limiting draw ratio, LDR, becomes larger. The plastic-strain radio is obtained by taking a tensile specimen and straining it to the point of necking. The longitudinal, thickness, and lateral (with-direction) strains are determined and are, respectively, ε_l, ε_t, and ε_w. The plastic-strain ratio is defined as:

$$r = \frac{\varepsilon_w}{\varepsilon_t}$$

ASTM E 517 describes the test used to determine *r*. The limiting draw ratio (LDR) is the largest ratio of blank diameter to punch diameter for which the blank can be drawn into a cup of diameter D_p without tearing.

Many laboratory tests have been developed to measure and control the formability characteristics of sheet metals. Some, such as the hydraulic bulge test, are fundamental tests, while others attempt to simulate actual sheet-forming operations. Finally, the forming of actual parts on which a grid of circles has been imprinted in combination with the forming-limit curves (or Keeler-Goodwin curves) can be used to measure the formability of a given sheet metal.

In the hydraulic bulge test, metal is tested under uniaxial tension in the tension test and under local compression in the hardness test. In a typical press-forming operation, the metal is deformed under biaxial tension or biaxial tension-compression, in which the metal is strained simultaneously in two directions in the plane of the sheet. The hydraulic bulge test can be used to measure the properties of sheet metal when strained under biaxial conditions.

In the bulge test, a circular sheet is clamped at the edge and deformed by hydraulic pressure into a dome. For an isotropic sheet, essentially uniform biaxial stress and strain exist over an appreciable region at the center of the diaphragm. Failure eventually occurs in this central region.

Another sheet-formability test is the stretch bend test, which measures the ability of a sheet metal to be bent around a sharp radius under tension. It is a more severe test than the simple bend test and, in addition, can be used to measure the sensitivity of a metal to tearing from a stretched cut edge (a major problem in components with hole or stretch flanges).

In the stretch bend test, a sheared strip specimen of the material to be tested is clamped firmly between jaws and bent under tension, burr side outward, over a radiused punch. Normally, an autographic record of punch load and punch travel is obtained during the test. The punch travel--either at maximum load when cracks start to run into the material from the sheared edges, or at failure--is taken as the measure of specimen formability.

Ball Punch Deformation Test (Olsen and Erichsen Tests)

The Olsen test simulates sheet-metal performance under stretching conditions. It is a simple test in which the sheet metal is clamped rigidly in a blankholder, then stretched over a small hemispherical punch 22.2 min ($\frac{7}{8}$ in.) in diameter. The stretchability of the sheet is then assessed by measuring the height to which the sheet can be stretched before fracture occurs. In a typical Olsen tester, both the punch travel and punch load are recorded, and the fracture point is established by noting the point at which the load suddenly decreases. Figure 58 shows sheet specimens that were subjected to four different formability tests.

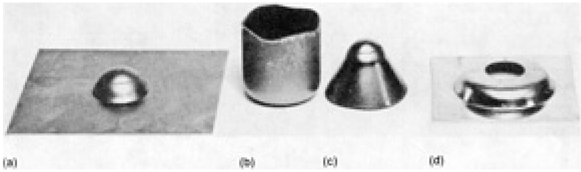


Fig. 58 Results typical of ductility tests on sheet-metal blanks. (a) Olsen and Erichsen tests. (b) Deep draw cup test. (c) Fukui test. (d) Hole-expansion test. Courtesy of Tinius Olsen Testing Machine Co.

The Olsen test has been replaced by the "ball punch deformation test" standardized by ASTM (ANSI/ASTM E 543). In this test, many of the test parameters that previously were left to the discretion of the individual performing the test are normalized. The standardized test applies to specimens with thicknesses between 0.2 and 2.0 mm. The machine to which the tooling is attached should have the capability of holding down the specimen (pressure between the top and bottom die) with a force of at least 10,000 N (2200 lbf).

Because the punch surface and the sheet-metal surface are in contact during this test, the friction between the two surfaces has a large effect on the test conditions. To maintain standard friction conditions from one test to the next, the lubricant is standardized. Commercial available petroleum jelly is applied to the punch only. ASTM E 643 also states that other lubrication systems (e.g., polyethylene sheet plus oil) may be used as agreed between supplier and user.

The speed of the penetrator shall be between 0.08 and 0.4 mm/s (0.2 and 1 in./min). The end of the test corresponds to the drop-in load, which is caused by necking of the sheet. If the machine is not equipped with a load indicator, the end point will be either visible necking or fracture of the test specimen in the dome. The cup height is measured at this point and is the penetrator (punch) displacement.

The Erichsen test, which is common in Europe where it was standardized, is similar to the Olsen test in principle--that is, the test simulates sheet-metal performance under stretching conditions. The punch diameter for the Erichsen test is slightly smaller than the punch used for the Olsen test (20 mm, or 0.79 in.).

The Erichsen test may be performed with or without lubrication, but the use of lubrication introduces a new variable, as described in the above discussion of the Olsen test. A portable instrument for performing the Erichsen test is available and has been widely used for control of formability or drawability in sheet-metal working, especially for quality control of incoming material.

Limiting Dome Height Test

In the Erichsen, Olsen, and bulge tests, fracture occurs at conditions that are close to equibiaxial strain (when the strain is the same in the two perpendicular directions). In the uniaxial tension test, fracture occurs at a combination of tensile strain plus a small amount of contraction strain in the width direction. In practical press-forming operations, most fractures occur at close to plane-strain conditions, such as a tensile strain in one direction with zero strain in the other direction--which is somewhere between the, conditions in the Olsen, Erichsen, and bulge tests on the one hand and conditions in the tension test on the other.

The limiting dome height test has been developed to simulate more effectively the fracture conditions found in most parts. In this test, a large-diameter hemispherical punch, usually 100 mm (4 in.) in diameter, is used, and strips of sheet steel of varying widths are clamped and then stretched over the punch. The strips are marked with a grid of small circles, 2.5 mm (0.1 in.) in diameter, and the width strain at fracture is measured from the circle closest to the fracture. The width strain increases as the width of the sheet becomes greater.

The advantage of the limiting dome height test is that it more closely simulates the fracture conditions in a practical press-forming operation. It is a complex and time-consuming test, however, and the results are critically dependent on sheet thickness. In this test, lubrication is not critical; the standard practice is to perform the test dry (without lubricant).

Swift Cup Test

This test simulates the drawing operation and involves drawing of a small flat- or hemispherical-bottom, parallel-side cup. The sheet is held under a blankholder, as shown in Fig. 59, but is well lubricated with polyethylene and oil to ensure that the blank can be drawn in under the blankholder. Typical Swift cup test forming tools are available in 19, 32, and 50 mm diameters for use with specimens ranging in thickness from 0.3 to 1.24, 0.32 to 1.30, and 0.45 to 1.86 mm, respectively. For drawing 40 mm square cups from 80 mm diam round specimens from 0.2 to 2 mm thick, a 40 mm square forming tool is recommended.

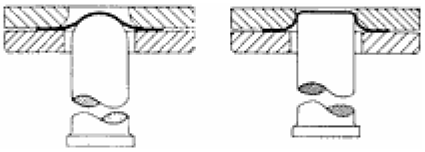


Fig. 59 Swift cut test. Punch diameter is 50 or 32 mm (2 or 1.3 in.).

The drawability of the metal is estimated by drawing a series of blanks of increasing diameter. The maximum blank size that can be drawn without fracture occurring over the punch nose is used to calculate the limiting draw ratio. For example, forming a 66 mm diam disk using a 33 mm forming tool provides an LDR of 2.0. Because the condition of the edge of each blank can have an important effect on the test result, the blank edges usually are turned in a lathe to ensure strain-free, burr-free edges.

The results of this test correlate well with the performance of sheet metal in deep-drawn components, but, because of shape and alignment, reproducibility between laboratories is not good. The main problem with this test, however, is that it is time consuming, and a large number of blanks of different sizes must be tested to obtain a reliable result.

Apart from measuring drawability, this test also can be used as a quality control check to measure the tendency toward earing of the sheet metal. In this case, a blank of fixed diameter is drawn, and the height between the peaks and troughs in the cup wall are measured.

The Englehardt or draw fracture test is a variation of the Swift cup test for measuring drawability that overcomes the problems of complexity and time involved in that test. The draw fracture test involves drawing of a cup to the point of maximum drawing load, then clamping the flange and continuing the punch travel to fracture. A load-penetration curve similar to that in Fig. 60 is obtained and the Englehardt value, T, is calculated from the maximum draw and fracture loads, P_d and P_f:

$$T = \frac{P_f - P_d}{P_f}$$

This result depends on strip thickness and usually is corrected, using an empirical relationship, to a nominal thickness. Because of its simplicity of operation and reproducibility, the draw fracture test is the most suitable for testing of drawability on a routine basis.

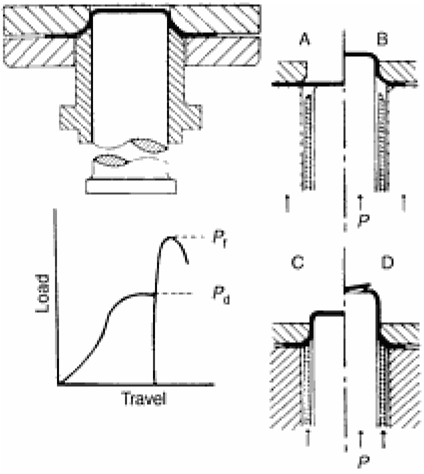


Fig. 60 Draw fracture test. A and B: drawing. C and D: clamping and fracture

Fukui Conical Cup Test

The Fukui conical cup drawing test (Fig. 61) was developed to assess the performance of a material during forming operations involving both drawing and stretching. The advantage of this test is that no holddown is necessary if the correct relationship between sheet thickness and blank diameter is maintained.

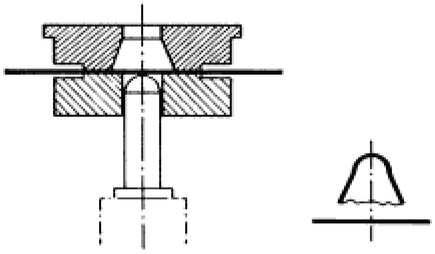


Fig. 61 Fukui conical cup test

A blank of the appropriate size is laid over a 30° conical entry die and forced into the cavity by a flat-bottom or hemispherical punch. The height of the cup at failure is used as a measure of formability. The test requires various tooling for different sheet thicknesses, and the result is thickness dependent. It has been demonstrated that the Fukui cup depth is influenced mainly by stretchability, but with some dependence on drawability. Thus, this test does not correlate as highly with uniform elongation and *r*-values as do other tests that are predominately stretch or draw, which may explain why the conical cup test has not been as widely accepted as other simulative tests.

Typical tooling commercially available for the Fukui test includes a cutting ring, cutting ram, and ball indenter available for specimen thicknesses from 0.5 to 1.6 mm.

Forming-Limit Curves

The poor correlation often found between results of the common "cupping" test and actual metal performance led investigators to look at some more fundamental parameters. Localized necking requires a critical combination of major and minor strains (along two perpendicular directions in the sheet plane). This concept led to the development of diagrams known as the Keeler-Goodwin or forming-limit curves. The forming-limit curve (FLC) is an important addition to formability testing techniques.

Each type of steel, aluminum, brass, or other sheet metal can be deformed only to a certain level before local thinning (necking) and fracture occur. This level depends principally on the combination of strains imposed, that is, the ratio of major and minor strains. The lowest level occurs at or near plane strain, that is, when the minor strain is zero.

This information was first represented graphically as the forming limit diagram, which is a graph of the major strain at the onset of necking for all values of the minor strain that can be realized. Figure 62 shows a typical forming limit diagram for steel. The diagram is used in combination with strain measurements, usually obtained from circle grids, to determine how close to failure (necking) a forming operation is or whether a particular failure is due to inferior work material or to a poor die condition.

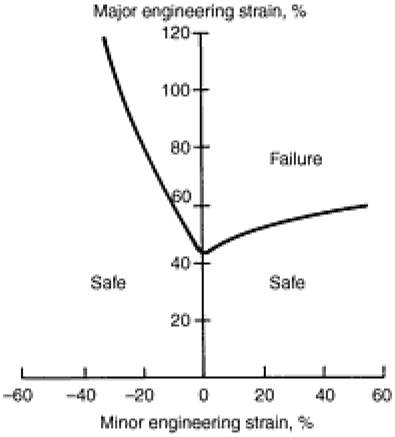


Fig. 62 Typical forming limit diagram for steel

For most low-carbon steels, the forming limit diagram has the same shape as the one shown in Fig. 62, but the vertical position of the curve depends on the sheet thickness and the *n* value. The intercept of the curve with the vertical axis, which represents plane strain and is also the minimum point on the curve, has a value equal to *n* in the (extrapolated) zero thickness limit. The intercept increases linearly with thickness to a thickness of about 3 mm (0.12 in.).

The rate of increase is proportional to the *n* value up to *n* = 0. 2, as shown in Fig. 63. Beyond these limits, further increases in thickness and *n* value have little effect on the position of the curve. The level of the forming limits also increases with the *m* value.

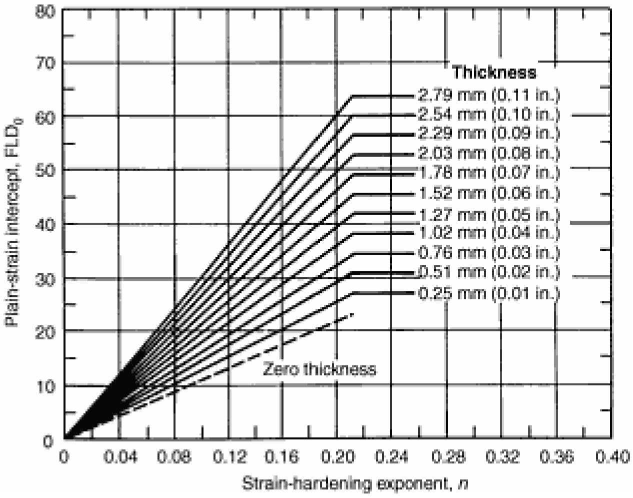


Fig. 63 Effect of thickness and *n* value on the plane-strain intercept of a forming limit diagram

The shape of the FLC for aluminum alloys, brass, and other materials differs from that in Fig. 62 and varies from alloy to alloy within a system. The position of the curve also varies and rises with an increase in the thickness, *n* value, or *m* value, but at rates that are generally not the same as those for low-carbon steel.

The forming limit diagram is also dependent on the strain path. The standard FLC is based on an approximately uniform strain path. Diagrams generated by uniaxial straining followed by biaxial straining, or the reverse, differ considerably from the standard diagram. Therefore, the effect of the strain path must be taken into account when using the diagram to analyze a forming problem.

These FLCs provide helpful guidelines for press-shop formability. Coupled with circle-grid analysis, they can serve as a guide in modifying the shapes of stampings. Circle-grid analysis consists of photoprinting a circle pattern on a blank and stamping it, thereby determining the major and minor strains in its critical areas. This is then compared with the FLC to verify the available safety margin. The strain pattern can be monitored with changes in lubrication, hold-down pressure, and size and shape of drawbeads and the blank; this can lead to changes in experimental procedure. Circle-grid analysis also serves, in conjunction with the FLC, to indicate whether a certain alloy might be replaced by another one, possibly cheaper or lighter. During production, the use of occasional circle-grid stampings provides valuable help with respect to wear, faulty lubrication, and changes in hold-down pressure.

Wear Testing

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Introduction

WEAR is mechanically-induced surface damage that results in the progressive removal of material. Because different types of wear occur in machinery, many different types of wear tests have been developed to evaluate its effects on materials and surface treatments. Consequently, the selection of the right type of wear test for each investigation is important in order to achieve useful and meaningful engineering data. More than one type of wear can attack the same part, such as sliding wear and impact wear in printing presses, or erosive wear and abrasive wear on extrusion machine screws for plastics. Sometimes wear can operate in the presence of corrosive or chemically-active environments, and synergistic chemo-mechanical effects are possible. Selection of appropriate wear test methods begins with an assessment of the type of wear involved in each problem area. Having a structure to classify wear types can make this process easier, and one such structure is provided in this article.

Wear testing is performed for one or more of the following reasons: to screen materials, surface treatments, or lubricants for a certain application; to help develop new, wear-resistant materials, surface treatments, or lubricants; to establish the relationship between the manufacturing, processing, or finishing methods applied to a certain machine part and its wear performance; or to better understand and model the fundamental nature of a certain type of wear. Surprising to some, the wear resistance of a given material is not a basic material property, like elastic modulus or yield strength. Rather, a material's wear behavior depends on the conditions of its use. Therefore, the first step in wear testing is to recognize how the results of the work will be used. Only then can the appropriate test method(s), testing parameters, and a useful format for reporting the results be selected. While this strategy may seem straightforward, its implementation in practice is not necessarily so.

A test intended to mimic the environment seen by a particular machine component is called a tribosimulation. The initial challenge in designing a tribosimulation is identifying the major wear-causing factors and finding a test that will produce the same type of wear response from test coupons as for operating parts. Conducting a tribosystem analysis involves gathering as much data as possible from the field, consulting the component designers, if possible, and attempting to define the relevant contact conditions (mechanical, thermal, and chemical) accurately.

Deciding which test to use and then selecting the proper variables and controls for that test often involves an iterative process of testing, analyzing the results, examining the worn surfaces, and possibly adjusting the testing parameters to better establish the usefulness and repeatability of the results. Because the subject of wear testing encompasses a wide variety of machine designs and testing strategies, this article focuses principally on the basic principles of wear test selection and use. The selected references listed in the bibliography provide additional detailed information, particularly when there is a need to screen materials for specific, wear-critical applications.

German standard DIN 50-322 elucidates a convenient method for grouping types of wear tests. The six levels of wear testing are as follow: (1) field testing (e.g., a truck for hauling rock), (2) full-scale machine test stand trials (e.g., the truck carrying a known load running on a wheel dynamometer stand), (3) machine subassembly test stand trials (e.g., the transmission of the truck on a dynamometer), (4) sub-scale tests (e.g., a small version of the transmission on a dynamometer), (5) component tests (e.g., a gear-testing machine), and (6) simple specimen tests (e.g., a simple curved specimen sliding on another curved specimen). Most laboratory wear tests, including a number of ASTM standard wear test methods, fall into categories (5) or (6). These bench-type tests are the focus of this article.

Wear Mechanisms

Before describing specific types of tests, it will be helpful to identify the major forms of wear. Different classification schemes for wear have been developed, because those developing wear classification schemes have come from different backgrounds and experiences with wear. No one scheme is universally accepted, but most of them have reasonably similar features. Figure 1 shows an approach to wear classification; here, wear is classified by the type of relative motion. Note that galling, scratching, scoring, and damage from the impact of a foreign body are not strictly forms of wear because material is not necessarily removed (it may instead be displaced to one side), and even if some material is removed, the process is not repetitive and progressive. Rather, these latter phenomena are referred to as "surface damage."

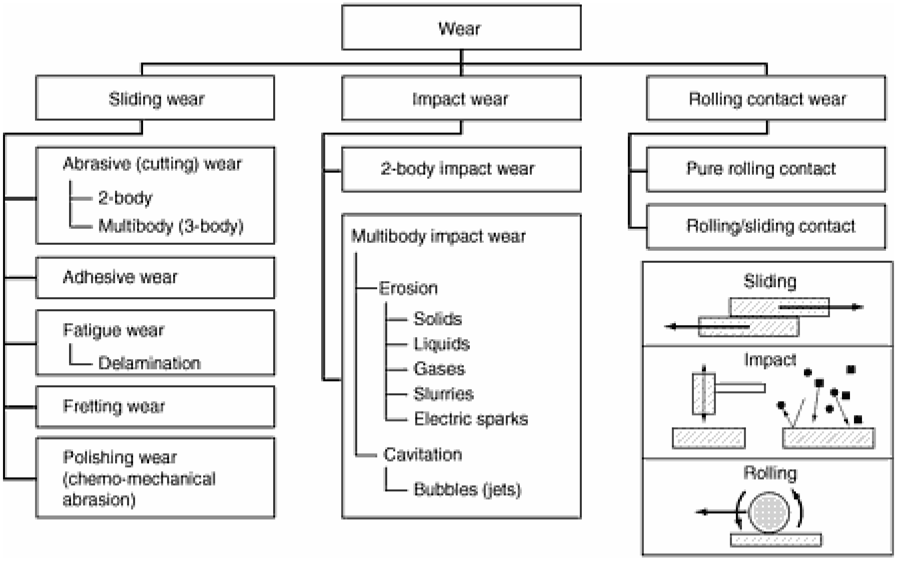

Wear
Sliding wear
Impact wear
Rolling contact wear
Abrasive (cutting) wear
2-body
Multibody (3-body)
Adhesive wear
Fatigue wear
Delamination
Fretting wear
Polishing wear (chemo-mechanical abrasion)
2-body impact wear
Multibody impact wear
Erosion
Solids
Liquids
Gases
Slurries
Electric sparks
Cavitation
Bubbles (jets)
Pure rolling contact
Rolling/sliding contact
Sliding
Impact
Rolling

Fig. 1 Major categories of wear

Forms of Wear

The three categories of contact depicted in Fig. 1 are tangential motion (sliding), impact, and rolling. There are a number of subcategories. Formal definitions for the important types of wear, such as those shown in Fig. 1, have been compiled from a variety of sources in the Glossary of *Friction, Lubrication, and Wear Technology,* Volume 18, *ASM Handbook.* The Glossary also contains reviews of each major form of wear and detailed discussions of both wear mechanisms and wear control. An abbreviated summary of the characteristics of the wear types shown in Fig. 1 follows.

Sliding wear is the consequence of relative tangential motion between solid surfaces being pressed together. If one of the surfaces is much harder and contains sharp points that plow or cut through the other surface, possibly producing thin chips, then two-body abrasive wear is said to occur. An example of this is sandpaper abrading wood. In contrast, three-body abrasive wear is produced by foreign particles trapped between relatively-moving solid surfaces. An example of this is the accelerated wear of a bushing by hard particles (grit) that have somehow found their way into the lubricant. It is possible that what starts out as a sliding wear situation can become a three-body abrasive wear situation after a period of time due to the generation and abrasive action of work hardened wear debris particles.

Adhesive wear is a somewhat archaic term, based on a proposed mechanism for the severe wear of metals, in which material from one surface is observed to adhere to the other at high spots (asperities) that are subsequently sheared off. While factors other than adhesion may be involved, it is so historically ingrained in the tribology literature that it will be used here for convenience to describe sliding wear other than the other than abrasive, fretting, fatigue, and polishing wear. Repeated stressing of a surface by sliding contact can cause cracks to nucleate and grow, producing the flake-like delaminations and pitting that are associated with fatigue wear. Fretting wear is a special case of reversed oscillating sliding wear in which the relative displacements between bodies are quite small (<50 to 150 μm), and the wear debris exhibits a characteristic powdery appearance. Likewise, polishing wear is a special case of three-body abrasive wear that can involve chemical as well as mechanical aspects of fine-scale material removal.

In impact wear, there is a repetitive impulse component normal to the wearing surface. One example of two-body impact wear is a mechanical printing plate repeatedly striking the paper. Thus, impact wear generally produces surface fatigue. Impact wear may also occur in combination with sliding wear, as in the case of a type face striking the surface of a moving printer ribbon or when the tip of a jet engine turbine blade impacts and rubs on its surrounding shroud.

Multibody impact wear can be further broken down into erosive wear and cavitation wear (or cavitation erosion). Erosive wear involves the cumulative effects of many particles striking a surface. These particles can be solids, liquid droplets (e.g., rain), collapsing bubbles, or solid-liquid mixtures called slurries. Electric sparks can also cause erosion, as in the opening and closing of electrical contacts carrying high currents. Cavitation or cavitation-erosion is caused by the collapse of tiny bubbles against a solid surface submerged in a liquid. This situation occurs in pumps and high-pressure piping. The noise of cavitation is a concern to those who build automotive fluid pumps and the propellers of "quiet" submarines.

Rolling Contact Wear. The rolling of one body over another, as in a rolling element bearing, can result in repeated stressing of the subsurface material, the nucleation of microcracks, and the eventual production of pits and spalls. Analysis of bearings and gears indicates that some degree of slip occurs in many rolling contact situations, such as in the cam and roller assembly in an automobile valve train and in the engagement of gear teeth. Thus, it is common to observe sliding wear features (e.g., scuffed or polished-looking areas) on components that are ordinarily considered to be in "rolling contact." The degree to which sliding governs the total wear of components must be ascertained in individual cases, but there are wear tests that have been developed specifically to permit the proportion of rolling to sliding contact (slide/roll ratio or percent slip) to be adjusted.

Causes of Wear

Wear is one of the ways in which the surface of a solid body can dissipate energy that is being externally supplied to it. Figure 2 schematically shows how the mechanical energy into a surface can be partitioned. In sliding contact, the product of the kinetic friction force, F, and relative velocity, v, equates to work into the surface per unit time (e.g., N · m/s or lbf · ft/min). The kinetic friction force is, by definition, the product of the kinetic friction coefficient (μ_k) and the normal force, P. Therefore, most models for frictional heating include $F \cdot v$ or $\mu_k \cdot F \cdot v$; however, not all of the frictional energy turns into heat. It is the part that goes into forming new surfaces and deforming and fracturing the surface material that is addressed here. Energy can also be supplied, for example, from the impact of small particles (erosive wear) or larger bodies repetitively impacting the surface (impact wear).

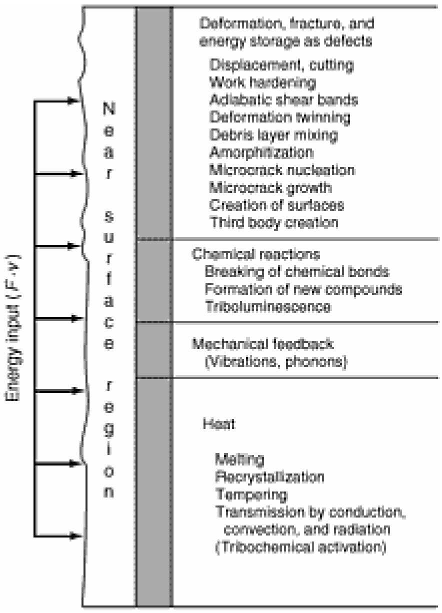

Energy input (F · v)
Near surface region
Deformation, fracture, and energy storage as defects
Displacement, cutting
Work hardening
Adiabatic shear bands
Deformation twinning
Debris layer mixing
Amorphitization
Microcrack nucleation
Microcrack growth
Creation of surfaces
Third body creation
Chemical reactions
Breaking of chemical bonds
Formation of new compounds
Triboluminescence
Mechanical feedback
(Vibrations, phonons)
Heat
Melting
Recrystallization
Tempering
Transmission by conduction, convection, and radiation
(Tribochemical activation)

Fig. 2 Distribution of energy from surface contact

The shaded bar in the Fig. 2 represents the partition of the available energy. In all likelihood, most of the energy is converted into heat, but the relative proportion going into the other categories is a function of the specific tribosystem configuration and the materials involved. Therefore, even if two different pairs of materials exhibit the same friction coefficient, their relative wear rates could be much different, because the available frictional energy is not being partitioned in the same way in both couples. A good wear-resistant material should dissipate heat well, but not use the energy input to create new surfaces (i.e., minimize the energy going into fracture, plastic deformation, or micro chip cutting).

Measuring Wear and Reporting Wear Test Results

The units selected for measuring and reporting wear and wear rates will depend on the type of wear being measured, the total mass or volume of wear typically generated from the given type of test, and the geometry and size of the test specimens. In tribosimulation work, there is an additional consideration of providing a measure of wear that best corresponds to the manner in which wear is determined on the parts being simulated. Often, however, the wear volume or wear mass loss is not well quantified in the field. Instead, wear out is based on visual inspection or on some other adverse characteristic of the machine behavior, like wear particles in the lubricant, higher vibration levels, or fluid leakage. Thus, it is not always possible to directly relate numerical wear data obtained in laboratory studies to component behavior. Alternative criteria for wear acceptability include the appearance (roughness) of the contact surface and the ranking of reference ("benchmark") materials in the laboratory in the same order as they rank in field trials.

Wear rates are combinations of units that can express either a normalized or relative figure of merit. The general form of a wear rate is a fraction in which the numerator corresponds to the mass, length, or volumetric quantity of wear, and the denominator represents one or more normalization parameters, or alternatively, the wear quantity for a reference material tested under the same conditions. An example of the former is a wear factor for sliding wear: volume of material lost per unit of applied normal force per unit of distance slid, $mm^3/N \cdot m$. An example of the latter is mass loss of the material of interest per unit sliding distance divided by mass loss of a reference material per unit sliding distance. In particle impingement erosion testing, the wear rate is often expressed as mass of material lost per unit mass of particles impacting the surface (g/g). In that case, the quantity first appears to be dimensionless (g/g), yet it is not so, because grams of specimen material are not the same as grams of erodant material.

Implicit in the use of wear rates is the assumption that those wear rates are linear with respect to the quantities in the denominator, notably sliding distance or time of contact. In fact, several types of wear, like sliding wear and solid particle erosive wear, do not experience linear wear rates throughout their histories. For example, running in (wear in) can occur in newly replaced bearings. The initial wear rate in that case is many times higher than the steady-state wear rate. In consideration of such effects, it is sometimes useful to subject the test specimens to a standard running-in or conditioning period and then make the first wear measurement, continuing the experiment for another time period to make a second measurement. This practice will help establish the steady-state wear rate of the material system and will not be affected so greatly by running-in phenomena. In other cases, it is important to know the total amount of wear of the material, including the pre-steady-state wear. Testing results should indicate whether the total wear or the steady-state post-running-in wear was used in computing the wear rates.

Table 1 lists common units for reporting the quantities and rates of various wear types. Common techniques used to measure wear include measuring the length or thickness change of the test specimen, profiling surfaces to determine the wear depth or cross-sectional area worn away, using a precision balance to measure mass loss, measuring the relative displacement of specimens on the testing machine (in situ) with a mounted sensor of some type, and making measurements of wear scar dimensions with microscopy. Other, less common methods include making replicas of surfaces before and after testing, placing hardness impressions in surfaces, and measuring the change in their sizes after wear. Lubricant filtration or ferrography (see the article "Lubricant Analysis" in *Friction, Lubrication, and Wear Technology,* Volume 18, *ASM Handbook*) is also a method to measure wear, as is surface layer activation by radionulcides.

Table 1 Common units for reporting wear and wear rates

Wear category	Subcategory	Wear quantities	Wear rate quantities
Sliding	Abrasive, two-body	M, V, D	$\mathrm{M} \cdot P^{-1} \cdot X^{-1}, V \cdot t^{-1}, M \cdot t^{-1}, M \cdot M_{\mathrm{ref}}^{-1}, V \cdot V_{\mathrm{ref}}^{-1}$
	Abrasive, three-body	M, V, D	$\mathrm{M} \cdot t^{-1}, D \cdot t^{-1}, M \cdot M_{\mathrm{ref}}^{-1}, V \cdot V_{\mathrm{ref}}^{-1}$
	Sliding, uni-directional	M, V, D	$\mathrm{M} \cdot P^{-1} \cdot X^{-1}, V \cdot t^{-1}, M \cdot t^{-1}, V \cdot X^{-1}, M \cdot X^{-1}, M \cdot M_{\mathrm{ref}}^{-1}, V \cdot V_{\mathrm{ref}}^{-1}$
	Sliding, reciprocating	M, V, D	$\mathrm{M} \cdot P^{-1} \cdot X^{-1}, M \cdot P^{-1} \cdot N^{-1}, V \cdot t^{-1}, M \cdot t^{-1}$
	Fretting	V, SR	. . .
	Polishing wear	M, V, D, SR	$\mathrm{M} \cdot t^{-1}, D \cdot t^{-1}$
Impact	Two-body	M, V, D, SR	$\mathrm{V} \cdot t^{-1}, M \cdot t^{-1}, V \cdot N^{-1}, M \cdot N^{-1},$
	Erosion, solid particle	M, V, D, SR	$\mathrm{M} \cdot M_{\mathrm{p}}^{-1}$, various quantities based on erosion-time curves (see ASTM test method G 32 for description)
	Cavitation	M	$\mathrm{M} \cdot t^{-1}$
Rolling	Rolling contact fatigue	$T_{\mathrm{ind}}, N_{\mathrm{f}}$	L_{10}
	Rolling with slip	$t_{\mathrm{ind}}, N_{\mathrm{f}}$	. . .

D = length or dimenional change, L_{10} = rating life in millions of revolutions or hours at a given operating speed and load that 90% of a given lot of bearings will survive, M = mass loss of the specimen, M_{p} = mass of impinging particles, M_{ref} = mass loss of a specified reference material under the same conditions, N = number of cycles or number of impacts, N_{f} = number of cycles to failure indication, P = normal force (load), SR = surface roughness, t = time of exposure to wearing conditions, t_{ind} = time to indication of problem (for example, noise or vibration level), V = volume of material lost, V_{ref} = volume of material lost by a reference material tested under the same conditions, X = total length of contact (sliding distance)

Each measure of wear has limitations in both its precision and accuracy. Table 2 shows the results of an experiment in which sliding wear of a specimen was measured by three independent methods. Tests involved sliding polished aluminum bronze blocks against a rotating bearing steel ring in argon gas. Wear was assessed by weight change, the depth of the wear scar (using a mechanical stylus), and optical microscope measurement of the width of the wear scar. Four replicate block specimens were tested, each sliding on a new ring. On closer examination of the measurement methods, a number of assumptions and potential sources of error are found. In using weight measurement, it is assumed that the specimens were completely cleaned of wear debris deposits before weighing and that the correct figure for the density of the bronze test specimen has been chosen. The following possibilities are also ignored: some of the steel wear particles adhesively transfer to the bronze specimen adding to its weight, there is some adsorption of ambient species onto the specimen surfaces, and oxides form as a result of the wear exposure. In using depth data, it is assumed that there are no adherent deposits of debris on the bottom of the wear scar. In using a microscope to measure wear scar dimensions, a judgment must be made as to where to place the cursor across the edges of the scar, which may in reality be irregular. Furthermore, it is assumed in calculating volume from scar width that the scar has a cylindrical shape. Had wear been measured by a displacement sensor, it would be important not to introduce significant error by allowing trapped deposits of wear particles in the interface to force surfaces apart. On the scale of micrometers or milligrams of total wear loss, such considerations can lead to significant errors in wear volume measurement. Considerations like this are particularly important in measuring the wear of thin coatings where the amount of material lost during the test is quite small.

Table 2 Comparison of three different methods for measuring the wear of block-on-ring specimens

Method	1	2	3	4	Average, mm^3
Mass loss, g	0.162	0.173	0.212	0.185	0.183
Wear width, mm	0.283	0.264	0.349	0.268	0.291
Scar depth, μm	0.245	0.275	0.256	0.228	0.251

The original raw data in these units were converted to volume in order to compare the four methods. Weight loss was divided by density of the bronze specimen to obtain volume. Scar depth was converted to cross-sectional area, assuming a contact curvature equal to the ring specimen radius, and multiplied by scar length to obtain volume. Scar width was converted to the cross-sectional area of a cylindrical segment and multiplied by scar length to obtain volume. Source: P.J. Blau, Needs and Challenges in the Precision Measurement of Wear, *J. Test. Eval.,* Vol 25 (No. 2), 1997

Each type of wear test method lends itself to certain techniques of wear measurement. Provided that systematic errors can be eliminated, the importance of conducting multiple tests to improve confidence in the results becomes obvious. It should also be noted that even if the accuracy of wear testing methods and metrology can be refined to a high degree, the ultimate limiting factor is the variability of the material behavior itself. In summary, the sources of variations in wear data can be related to the testing machine characteristics, the method of wear measurement, intrinsic material variations, and sometimes the operator's judgment in making measurements.

Tribosystem Analysis and Test Method Selection

In order to screen materials or lubricants for a certain application, a tribosystem analysis of the component of interest should be conducted. The following should be considered:

- The nature of relative motion (unidirectional, reciprocating, combined motions, etc.)
- The contact loads and/or contact pressures
- The speed of relative motion and its level of constancy
- The contact geometry of the wearing surfaces
- The temperature and chemical environment of the contact zone
- Whether third-bodies play a part, and if they do, their characteristics
- The method of surface preparation and cleaning
- The duration of exposure to wearing conditions
- Other requirements, such as cosmetic considerations, corrosion resistance, and fatigue strength
- The most important form(s) of wear and characteristic surface features that are present

In non-component-specific cases, such as the development of a new wear-resistant material, surface treatment, or lubricant that might have a variety of potential applications, it makes sense to conduct more than one type of wear test. A suite of tests will help to define the conditions for which a particular material is best suited. Conducting several types of wear tests on the material will also suggest a range of applications that might be promoted and reveal other situations that are less promising. The same set of materials can rank in opposite order when exposed to different types of wear.

Test Methods

Standardized Wear Testing Methods. The use of standard testing methods will not meet everyone's needs for wear data; however, if a tribosystem analysis suggests that an existing standard test method will be appropriate, the following advantages will ensue:

- Any new test results will be comparable with historical data obtained under the same conditions.
- Standards, such as ASTM standard test methods, involve a rigorous certification and validation process that identifies the important test variables and environmental factors that must be controlled to assure repeatability.
- Standards documentation provides excellent guidelines for assessing the significance of wear test results and indicates the potential sources of variability.
- Standard test methods could be used for routine quality control testing.

Organizations such as ASTM, the International Organization for Standardization (ISO), and the Society of Automotive Engineers (SAE) have standardized some kinds of wear tests. Most ASTM wear test methods were developed by committees D-2 on Lubricants and G-2 on Wear and Erosion. Unfortunately, standard test methods do not exist for all of the forms of wear shown in Fig. 1. Some of the existing standards are designed for specific applications while others are more generic and involve simple geometries.

A list of ASTM wear test methods, organized by type of wear and surface damage, is given in Table 3. These standards were developed by more than one autonomous standards-writing subcommittee within the society and vary in the means specified for preparing test specimens, precleaning them, measuring wear, and reporting the data. Thus, even wear standards are not standardized in that sense. This should not be surprising in light of the many forms of wear and the many types of materials that are used in wear applications. If a suitable standard test method cannot be found in the literature, an organization may decide to develop its own internal wear-testing standards best suited to its purposes.

Table 3 ASTM wear test methods grouped by wear type

Form of wear	Designation	Title	Means of wear measurement
Abrasive wear, 2-body	G 56	Test Method for Abrasiveness of Ink-Impregnated Fabric Printer Ribbon	Surface profiling or other method
	G 132	Test Method for Pin Abrasion Testing	Mass loss
	G 119	Guide for Determining Synergism between Wear and Corrosion	Mass loss and corrosion-related measurements
Abrasive wear, 3-body	G 65	Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus	Mass loss
	G 81	Practice for Jaw Crusher Gouging Abrasion Test	Mass loss ratio
	G 105	Test Method for Conducting Wet Sand/Rubber Wheel Abrasion Tests	Mass loss, normalized by wheel dimensions
Erosive wear, cavitating fluid	G 32	Test Method for Cavitation Erosion Using Vibratory Apparatus	Mass loss
Erosive wear, liquid droplets	G 73	Practice for Liquid Impingement Erosion Testing	Mass loss
Erosive wear, slurry	G 75	Test Method for Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Resistance Response of Materials (SAR Number)	Mass loss
Erosive wear, solid particles	G 76	Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets	Mass loss
Fretting wear	D 4170	Test Method for Fretting Wear Protection of Lubricating Greases	Mass loss ratio
Sliding wear	D 2266	Test Method for Wear Preventative Characteristics of Lubricating Grease (Four-Ball Method)	Wear scar diameter
	D 2670	Test Method for Measuring Wear Properties of Fluid Lubricants (Falex Pin and Vee Block Method)	"Teeth wear"--apparatus-specific measurement of wear
	D 2882	Test Method for Indicating Wear Characteristics of Petroleum and Non-Petroleum Hydraulic Fluids in a Constant Volume Vane Pump	Mass loss
	D 2981	Test Method for Wear Life of Solid Lubricants in Oscillating Motion	Number of revolutions to failure, as indicated by friction
	D 3702	Test Method for Wear Rate of Materials in Self-Lubricated Rubbing Contact Using a Thrust Washer Testing Machine	Thickness change
	D 3704	Test Method for Wear Preventative Properties of Lubricating Greases Using the (Falex) Block on Ring Test Machine in Oscillating Motion	Wear scar width

	D 4172	Test Method for Wear Preventative Characteristics of Lubricating Fluid (Four-Ball Method)	Wear scar diameter
	D 5001	Test Method for Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE)	Wear scar diameter
	G 77	Test Method for Ranking Resistance of Materials to Sliding Wear Using Block on Ring Wear Test	Wear scar width
	G 99	Test Method for Wear Testing with a Pin-on-Disk Apparatus	Ball: wear scar diameter, disk: profile
	G 119	Guide for Determining Synergism between Wear and Corrosion	Mass loss and corrosion-related measurements
	G 133	Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear	Ball: wear scar diameter, flat: profile
	G 137	Test Method for Ranking Resistance of Plastic Materials to Sliding Wear Using a Block-on-Ring Configuration	Mass loss
Surface damage, galling	G 98	Test Method for Galling Resistance of Materials	Visual inspection, critical load for galling
Surface damage, scoring	D 2782	Test Method for Extreme-Pressure Properties of Lubricating Fluids	"OK" value of maximum mass (weight) for load just below critical scoring condition

Variables to be Controlled in Wear Testing. Each wear mode is influenced by a different set of physical variables. Therefore, it is important to recognize what factors must be controlled, or at least monitored, in the design of wear testing procedures. As noted before, valuable guidance can be found in the literature and in standards documents. Table 4 lists the major experimental variables that are controlled in conducting wear tests of various types. Environmental and other factors, which should be considered in interpreting the results of the wear tests, are also listed. Sometimes these secondary factors must be controlled in order to simulate a given application, but usually it is sufficient just to measure and document them as an aid to interpreting the data.

Table 4 Parameters that are commonly controlled and reported when conducting wear tests of various types

Category	Subcategory	Typical variables	Supplementary characterizations or variables(a)
Sliding	Abrasive wear, 2-body	Load (contact pressure), abrasive type, binder type, backing body, whether repeated contact or sliding against fresh abrasive lubricant or coolant, surface speed, temperature, duration of contact	Method of surface preparation, material characterization
	Abrasive wear, 3-body	Load (contact pressure), abrasive type, concentration, hardness of counterbody(b), coolant or lubricant, whether repeated contact or continual motion against fresh abrasive surface, surface speed, temperature, duration of contact	Method of surface preparation, material characterization
	"Adhesive"	Load (contact pressure or stress), relative velocity, contact geometry, type of motion (unidirectional or oscillating), duration, sliding distance, or time of sliding, temperature	Method of surface preparation, cleaning, surface finish of bodies, type of material/lubricant, method of supplying the lubricant, relative humidity
	Fretting wear	Load (contact stress), contact geometry, amplitude of oscillation, frequency of oscillation, number of cycles or time, choice of lubricant	Surface finish, relative humidity, debris characteristics
	Polishing wear	Size of polishing medium, concentration of medium, liquid used for suspension, normal pressure, type of motion bodies (platten and specimen), time of exposure, temperature, substrate (pad type)	Particle composition and geometric description, method of medium introduction, initial surface finish of specimen
Impact	2-body	Force of impact, speed of impact, geometry of contact, angle of impact, repetition rate, duration/number of impacts, temperature	Material characterization, environment and relative humidity, surface finish of bodies
	Impingement, liquid and solid	Average impact velocity, particle stream shape (by nozzle design), impingement angle of the stream to the surface, duration of exposure, temperature of the specimen and/or jet	Particle velocity or flux distribution, density of particles, particle shape description, particle size distribution, particle composition
	Cavitation erosion	Test geometry, frequency of moving body oscillation, temperature of the fluid, fluid type, duration of exposure	Material characterization
Rolling	Rolling contact	Load (elastic contact stress), rpm of roller(s), test duration,	Lubricant/material characterization, surface

	fatigue	temperature	finish of rollers
	Rolling with slip	Load (elastic contact stress), rpm of roller(s), % slip, test duration, temperature	Lubricant/material type, surface finish of rollers

(a) These quantities are often used to characterize the testing conditions or materials even though they may not be directly controlled in an experiment. In certain cases, they could be treated as variables themselves.

(b) In certain types of 3-body abrasive wear tests, notably the dry sand-rubber wheel test, the hardness of the material that is pressing the loose abrasive particles against the test specimen can have a significant effect on the results.

One way to depict the influence of more than one variable at a time on a particular type of wear is through the construction of what are called "wear maps." Wear maps are graphical representations in which two or more independent variables are plotted against a third dependent variable, such as the wear rate or the dominant type of dominant wear mechanism. Wear rates or boundaries between dominating wear mechanisms are represented as families of curves or boundaries on the "map." Examples of the variables used in wear maps for sliding wear are load (or normal force or contact pressure) and velocity and for fretting wear, slip amplitude, and oscillating frequency. Many other combinations are possible, but it should be remembered that some of the variables are not completely independent of the others. For example, sliding velocity influences the temperature, and normal load can influence the sliding surface roughness. Figure 2 shows that the product of the load and velocity affects the energy to produce wear. The limit of usefulness for some bearing materials, notably polymers, are expressed in terms of a $P \cdot V$ (contact pressure times velocity) limit. When using or generating wear maps, the conditions used to obtain the data should be carefully considered so that unwarranted extrapolations of the data are avoided.

Specimen Surface Preparation and Cleaning. Test specimen surfaces should be prepared in such as way as to eliminate the possible effects of machining, grinding, and finishing processes. However, if the specimen is intended to screen a material for a certain application, then the surface finishing should be chosen to mimic that application. An additional consideration for tribosimulations is to make certain that testing is done in the proper orientation with respect to the grinding direction (lay). The relative sliding direction can affect the running-in process as well as the regime of lubrication, if one is running lubricated tests. Also, the methods of surface preparation and cleaning should be reported along with the other testing results.

The method of cleaning should not alter the chemistry of the test surface or cause it to be significantly abraded. Surface cleaning is particularly important in sliding wear tests in which friction will also be measured. The lower the contact force and the less abrasive the testing conditions, the more important is the cleaning procedure for obtaining reproducible friction and wear data. When running lubricated tests, soap and solvent residues could conceivably interfere with the action of lubricant additives and thus affect test results as well.

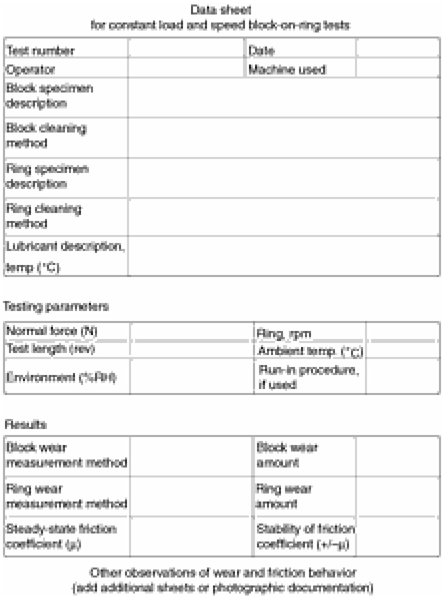
For cleaning metal and ceramic specimens, the following techniques have been used successfully. Rub lightly with a cotton swab saturated with acetone, then ultrasonically clean in methanol for 60 s, and dry with a hot air blower. Use a good grade of nonspotting laboratory glass cleaner, rinse in hot water, and hot air dry. Because oxidation, tarnishing, and/or recontamination of freshly cleaned specimen surfaces can occur under normal ambient exposure of most metals and ceramics, cleaning should be conducted immediately before testing or else the time between cleaning and testing should be controlled. In some cases, specimen surfaces can be rewiped with methanol after mounting them in the testing machine to ensure that handling smudges are removed. Store specimens to protect test surfaces.

Because polymeric materials can react with some solvents, some plastics are tested "as-received." In this case, it is doubly important to avoid touching the contact surfaces with the fingers during specimen preparation and mounting. In addition, thin films and surfaces covered with soft deposits should also be handled carefully to avoid disturbing the morphology and structure. Further guidance for specimen preparation and cleaning is provided in ASTM standard wear-testing methods.

Not only the specimens, but the test fixtures themselves should be kept clean and free of oil and grit. This detail is particularly important when conducting unlubricated tests but also applies to other situations. There are enough variables in wear testing without introducing additional problems from using oily or dirty testing machines.

Location of the Testing Machine. One factor that has been shown to cause problems in the repeatability and reproducibility of wear data is proximity of the wear testing machine to other machinery. For example, it is not advisable to locate a tester intended for dry sliding experiments right next to a lubricant testing machine because cross-contamination is possible. The same is true for locating wear testing machines in dirty areas of the plant when grit could become a problem. Vibrations have also been shown to affect friction and wear results. In summary, wear testing equipment should be treated much the same way in which quality control and precision metrology instruments are treated. Keep them clean, isolate them from vibrations, and avoid extremes of temperature and humidity. This extra care will accrue benefits in both the quality and repeatability of test results.

Proper documentation of wear testing procedures is important. Complete documentation is most helpful when comparing results to other tests or when trying to analyze the possible causes for differences in wear behavior among different materials. The widespread availability of computer spreadsheets and database programs linked directly to data acquisition systems makes test documentation easy after the initial set up. For example, Fig. 3 lists the type of information that might be incorporated into a computer data file for block-on-ring wear testing results. All ASTM standard wear test methods (Table 3) include a reporting section in which the important variables are delineated. In addition ASTM G 118 lists variables that may be reported. One advantage in using standard test methods is that once the method is specified, the applied testing parameters, such as normal force and length of test, are already implied and need not be redocumented.



Data sheet
for constant load and speed block-on-ring tests

Test number		Date	
Operator		Machine used	
Block specimen description			
Block cleaning method			
Ring specimen description			
Ring cleaning method			
Lubricant description, temp (°C)			

Testing parameters

Normal force (N)		Ring, rpm	
Test length (rev)		Ambient temp. (°C)	
Environment (%RH)		Run-in procedure, if used	

Results

Block wear measurement method		Block wear amount	
Ring wear measurement method		Ring wear amount	
Steady-state friction coefficient (μ)		Stability of friction coefficient (+/−μ)	

Other observations of wear and friction behavior
(add additional sheets or photographic documentation)

Fig. 3 Example of a reporting form for block-on-ring wear tests

Wear Testing Devices: Commercially Manufactured and Custom Made. As stated earlier, the diverse nature of wear has led to the design of many types of wear testing machines. Table 5 exemplifies the types of simple testing geometries common to evaluating the various forms of wear. While simple geometries, such as those in Table 5, represent one approach to testing, some of wear machines are either one-of-a-kind or highly specialized for simulating a particular application. Commercially manufactured sliding and rolling contact wear testing machines are available in a number of contact geometries (Fig. 4). Abrasion and erosion testing machines are also commercially available. Some testers, called "universal" or "multimode" testers, are configured to permit the user to change the contact geometry from, for example, block-on-ring to pin-on-disk, using accessory fixtures and drive mechanisms. Several manufacturers or retail sellers of wear testing machines advertise on the Internet and can be found through key-word searches.

Table 5 Typical testing geometries for wear tests of various types

Category	Subcategory	Testing geometry
Sliding	Abrasive wear, 2-body	Flat pin-on-rotating abrasive drum (spiral path), reciprocating pin-on-abrasive flat, flat pin-on-moving abrasive belt, traversing pin-on-abrasive disk (spiral path), twin rotating abrasive wheels
	Abrasive wear, 3-body	Dry sand fed between a rotating rubber wheel and a flat coupon, reciprocating flat pin-on-a plate in a slurry bath, block-on-rotating ring in a slurry bath, ball mill, or tumbling wear test
	"Adhesive"	Block-on-ring (flat or conformal face), pin-on-disk, double rub-shoe on rotating disk, reciprocating pin-on-flat, flat-on-flat (thrust washer), pin clamped between V-blocks, ball spinning on three flats (120° apart)
	Fretting wear	Oscillating pin-on-flat, pivoting ball-in-socket, clamped specimen on the sides of a tensile coupon
	Polishing wear	Flat specimen-on-vibrating lap, flat specimens in an orbital polishing or lapping machine
Impact	2-body	Repetitive "hammer"-on-flat
	Impingement, liquid and solid	Liquid jet aimed at the specimen, gas jet with entrained particles, spinning specimens through a gravity-fed stream of particles, centrifugal particle "slinger" apparatus
	Cavitation erosion	Oscillatory "horn" suspended above the specimen in a fluid, flowing fluid through a submerged nozzle aimed at the specimen
Rolling	Rolling contact fatigue	Disk-on-disk rolling contact (equal circumferential speed), rod spinning between three captive balls
	Rolling with slip	Disk-on-disk rolling contact (unequal circumferential speed)

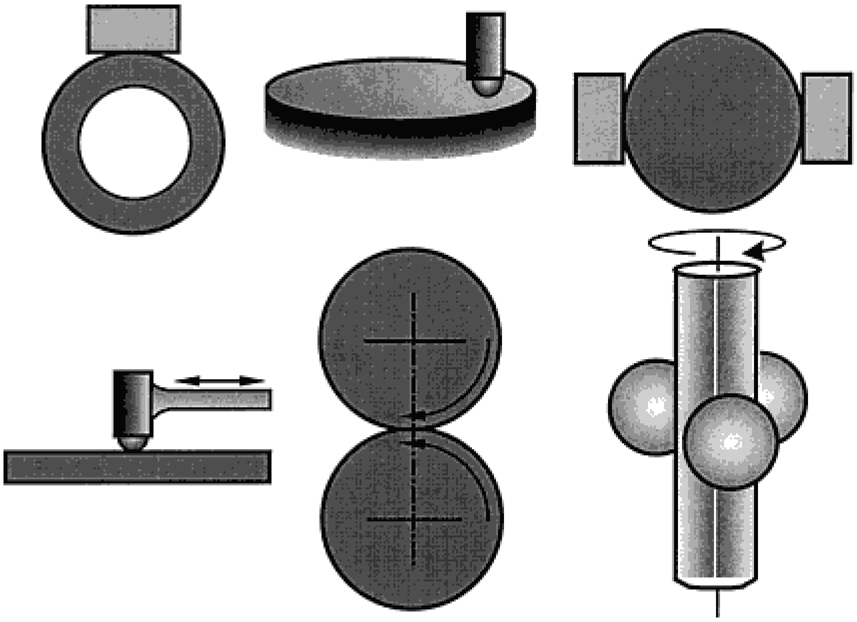


Fig. 4 Typical configurations of commercially manufactured wear testing machines

As indicated earlier, wear and chemical attack can have synergistic effects. Special procedures have been developed to study these phenomena (ASTM G 119). Specialized commercial testing machines have also been developed to study such effects, like machines that simulate the movements of surgical knee and hip replacement components in bodylike fluids.

As with mechanical testing in general, commercial wear testing machines are being computer automated. While automation has definite advantages, it also drives up the price of these machines. Testers with infrequent wear problems, or who do not want to make a significant capital investment in wear testing, may be faced with the decision as to whether to construct their own machine, purchase a commercial machine, have a custom machine built, or obtain the services of a fee-testing laboratory.

Published surveys, conducted years ago by organizations such as the American Society of Lubrication Engineers (now called the Society of Tribologists and Lubrication Engineers) and the European Space Agency, have revealed the existence of hundreds of different wear testing devices. Some of these devices have similar geometries and operational features; however, even relatively similar-looking machines can produce different wear results due to subtle differences in construction features (fixture stiffness, method of specimen mounting, mechanical damping capacity, natural frequencies, heat flow, etc.). The number of custom-designed wear testing devices probably exceeds the number of commercially produced machines. Unfortunately, people who decide to build their own wear testing machines may not be aware of certain subtleties in wear tester design and, thus, may ultimately generate questionable results or results that cannot be reproduced elsewhere. There is still a great deal of applied research needed to better understand differences in wear results arising from different machine designs and measurement techniques.

Summary

Select a wear testing method that meets the purposes for which the data are needed, and take steps to understand the characteristics and repeatability of results from the testing machine. The units used to report wear vary with type of wear and with the purpose for which the data are to be used. Screening materials for general wear-resistance or preparing a tribosimulation for a particular component involves careful study of the application and an analysis of the type of wear damage that occurs in service. Standards can provide both testing set-up information and the means to produce repeatable results. Documentation is also critical to allow the effective interpretation of the wear data. Whether to use commercially-available wear testing machines, contract wear testing, or develop customized testing equipment must be determined on a case-by-case basis from an examination of both economic and technical issues.

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Corrosion Testing

Tests for Stress-Corrosion Cracking

STRESS-CORROSION CRACKING (SCC) is a cracking phenomenon that occurs in susceptible alloys and is caused by the conjoint action of a tensile stress and the presence of a specific corrosive environment. For SCC to occur on an engineering structure, three conditions must be met simultaneously, namely, a specific crack-promoting environment must be present, the metallurgy of the material must be susceptible to SCC, and the tensile stresses must be above some threshold value. The tensile stress may be residual stress resulting from heat treatment or fabrication of the metal, may be developed by external loading, or may be a combination of these conditions.

Stress-corrosion cracking occurs under service conditions, which can result, often without any prior warning, in catastrophic failure. Many different mechanisms for SCC have been proposed, but in general, these mechanisms can be divided into two general groups, anodic dissolution mechanisms and cathodic mechanisms. The parameters that control SCC can be divided into materials, environmental, and mechanical parameters.

Stress-corrosion cracking failures resemble brittle fracture; typically there is little, if any, indication of metal ductility at the origin of fracture. The cracking actually is a form of subcritical flaw growth, either intergranular or transgranular, depending on the particular combination of microstructure, environment, and strain rate. However, it is more difficult to design against environmentally assisted cracking than against fracture. Reasons for this difficulty include the compositional, mechanical, and metallurgical synergism and the consequent need to consider a range of environmental variables, as well as their variations with time and their interactions with loading and metallurgical variables.

SCC Evaluation

In order to determine the susceptibility of alloys to SCC, several types of testing are available. If the objective of testing is to predict the service behavior or to screen alloys for service in a specific environment, it is often necessary to obtain SCC information in a relatively short period of time, which requires acceleration of testing by increasing the severity of the environment or the critical test parameters. The former can be accomplished by increasing the test temperature or the concentration of corrosive species in the test solution and by electrochemical stimulation. Test parameters that can be changed to reduce the testing time include the application of higher stresses, continuous straining, and precracking, which allows bypassing of the crack nucleation phase of the SCC process.

Stress-corrosion specimens can be divided into two categories: smooth specimens and precracked or notched specimens. Further distinction can be made in the loading mode, such as constant deflection, constant load, and constant extension or strain rate. These different loading modes will be discussed in more detail in the following sections.

During alloy processing operations used in the production of wrought alloys, the metal is forced in a predomination direction, so that the grains are elongated in the direction of flow. Because it is important to relate the application of stress and the grain flow direction, two conventions are used to relate the two parameters. In one system, which is primarily used for smooth specimens, the three stressing directions are designated by indicating the direction of the stress, namely longitudinal (L), long-transverse (LT), transverse (T), and short transverse (ST) (Fig. 1).

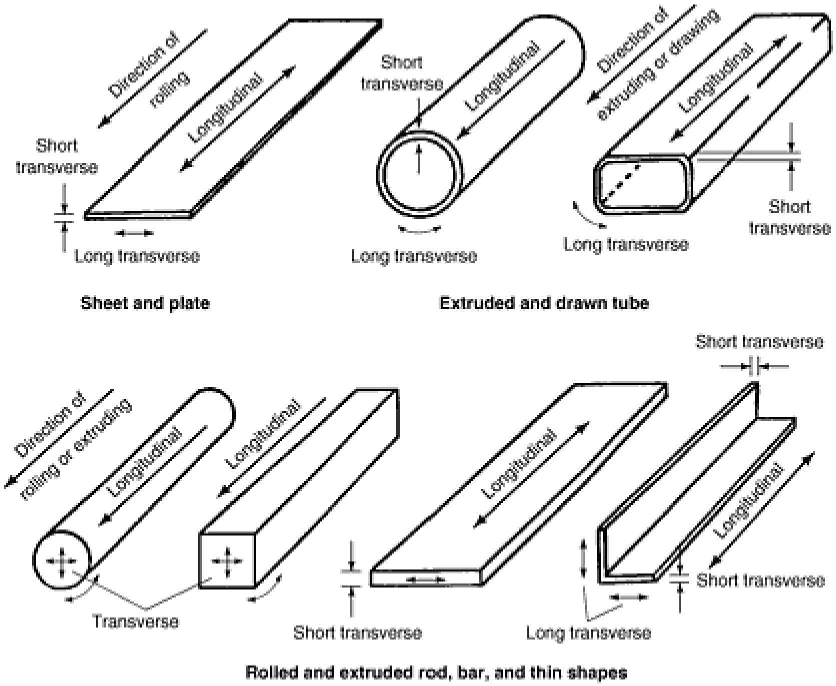
Direction of rolling
Longitudinal
Short transverse
Long transverse
Sheet and plate
Short transverse
Longitudinal
Long transverse
Direction of extruding or drawing
Longitudinal
Short transverse
Long transverse
Extruded and drawn tube
Direction of rolling or extruding
Longitudinal
Longitudinal
Transverse
Longitudinal
Short transverse
Short transverse
Longitudinal
Short transverse
Long transverse
Rolled and extruded rod, bar, and thin shapes

Fig. 1 Grain orientations in standard wrought forms of alloys

A second system, which is particularly useful for precracked specimens, indicates both the cracking plane and the direction of crack propagation. The system used three letters (L, T, and W) to indicate three perpendicular directions: L for the longitudinal direction, T for the thickness direction, and W for the width direction. The crack plane is indicated by the direction normal to the crack, and the crack propagation is indicated by one of the directions L, T, or W. Figure 2 demonstrates the various orientations for a double-cantilever-beam (DCB) specimen.

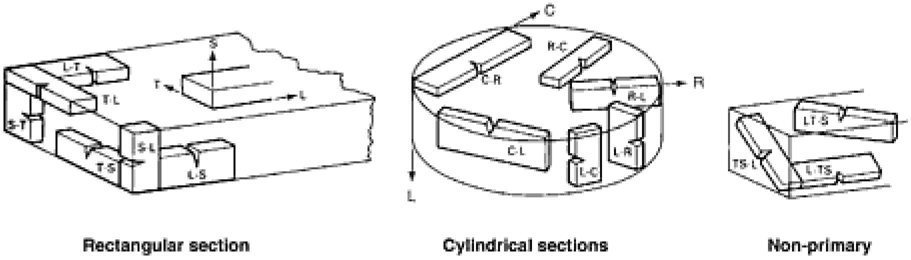
L-T
T-L
S-T
T-S
S-L
L-S
S
T
L
C
R-C
C-R
R
R-L
C-L
L-R
L-C
L
LT-S
TS-L
L-TS
Rectangular section
Cylindrical sections
Non-primary

Fig. 2 Fracture plane identification. L, direction of grain flow; T, transverse grain direction; S, short transverse grain direction; C, chord of cylindrical cross section; R, radius of cylindrical cross section; first letter, normal to the fracture plane; second letter, direction of crack propagation in fracture plane

Other parameters that play an important role in SCC testing are surface condition and residual stress. The nucleation of stress-corrosion cracks strongly depends on initial surface reactions, and thus the surface condition of the test specimens, particularly smooth specimens, has a significant effect on the test results. Smooth test specimens are often tested with a mechanically (machined or abraded) or (electro)chemically treated surface. It is very important to avoid or to remove machining marks or scratches perpendicular to the loading direction.

Smooth Specimen Testing

Smooth SCC specimens allow for the evaluation of the total SCC life, which includes crack nucleation and propagation. Testing can be conducted under constant extension or strain, constant load, and constant extension or strain rate. The selection of a specific test method for SCC strongly depends on the particular service application and the time allowed for testing.

Constant Extension Testing

Constant extension or constant strain tests on smooth specimens are widely used and do not require elaborate testing fixtures. Depending on the specific configuration of the test articles, different types of constant extension tests are being used. The most common types are bent-beam, U-bend, C-ring, and tensile type specimens.

Bent-Beam Specimens. The different types of bent-beam specimens are illustrated in Fig. 3. These specimens may be used to test sheet plate and flat extruded material, or wires and extrusions with a circular cross section. Figure 3 shows that the bending can be accomplished in several ways depending on the dimension of the specimen. Stressing of the specimen is accomplished by bending the specimen in a stressing device while restraining the ends. During stress-corrosion testing both specimen and stressing devices are exposed to the test environment. The most simple loading arrangement is the two-point loaded bent-beam, which can only be used on relatively thin sheet or wire material. The elastic stress at the midpoint of the specimen can be estimated:

$$L = (ktE/\sigma)\sin^{-1}(H/ktE)$$

where L is the specimen length, σ is the maximum stress, E is the elastic modulus, H is the length of holder, t is the specimen thickness, and k is the empirical constant (1.280).

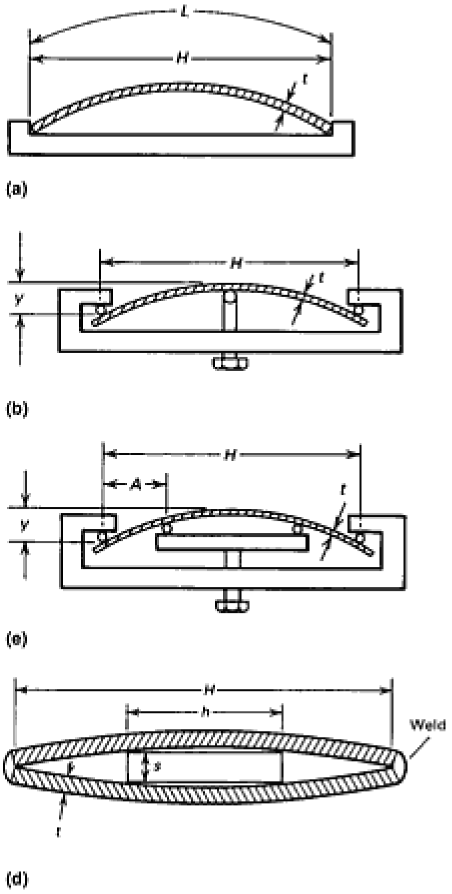

Fig. 3 Schematic specimen and holder configurations for bent-beam specimens. (a) Two-point loaded specimen. (b) Three-point loaded specimen. (c) Four-point loaded specimen. (d) Welded double-beam specimen

Three-point bend specimen tests are commonly used because of the ease of load application and the ability to use the same loading rigs for different stresses. The load is applied by turning a bolt in the rig, deflecting the specimen. The elastic stress at the midpoint of the specimen is calculated:

$$\sigma = 6Ety/H^2$$

where σ is the maximum tensile stress, E is the elastic modulus, t is the specimen thickness, y is the maximum deflection, and H is the length of holder.

This test has a number of disadvantages. First, dissimilar metal corrosion and/or crevice corrosion can occur under the bolt. Secondly, once the crack has formed, the stress condition changes such that the outer layer of the specimen is not subject to a tensile stress only but to a complex combination at tensile and bending stresses. The propagating crack will then deviate from the centerline. Thus, the three-point bend test can only be used as a qualitative test to assess the susceptibility to stress-corrosion cracking. With the four-point bend test, tensile stresses can be maintained during the growth of the crack.

Four-point bend specimen testing provides a uniform tensile stress over a relatively large area of the specimen. The elastic stress in the outer layer of the specimen between the two inner supports can be calculated:

$$\sigma = 12Ety/(3H^2 - 4A^2)$$

where σ is the maximum tensile stress, E is the elastic modulus, t is the specimen thickness, y is the maximum deflection, H is the distance between outer supports, and A is the distance between outer and inner supports.

U-bend specimens are prepared by bending a strip 180° around a mandrel with a predetermined radius (Fig. 4). The figure shows that bends less than 108° are also used. Standardized test methods are described in ASTM G 30. Because of the ease of fabrication, a large amount of specimens can be fabricated, and this test is therefore widely used to qualitatively evaluate the susceptibility of alloy and heat treatment to stress-corrosion cracking.

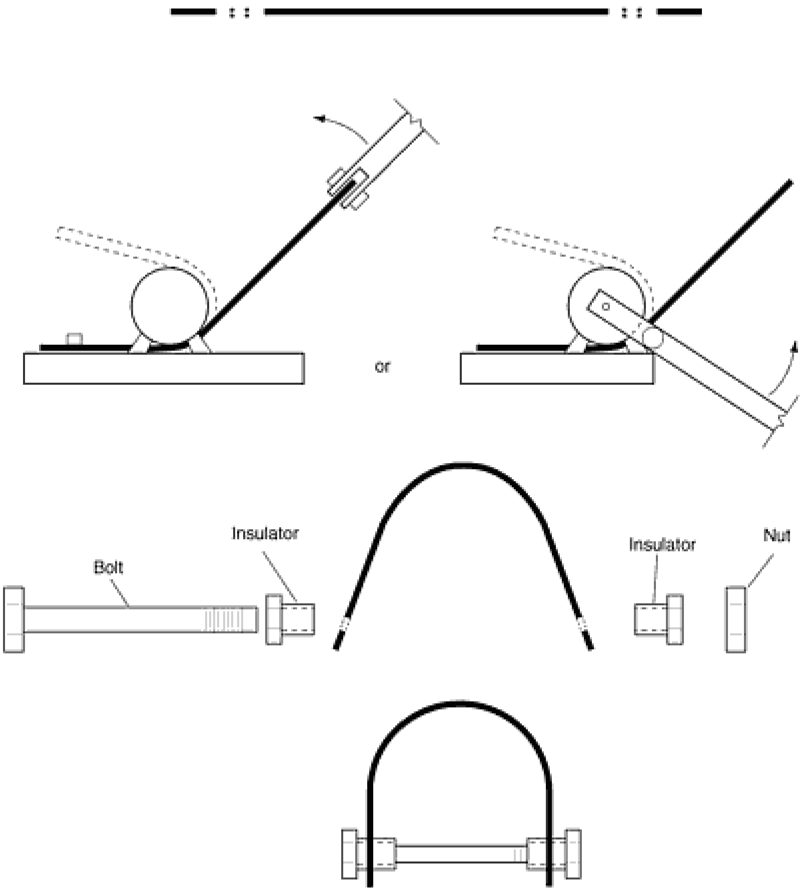

Fig. 4 Schematic two-stage stressing of a U-bend specimen

A good approximation of the strain at the apex of the U-bend is:

$$\varepsilon = t/2R, \text{ when } t < R$$

where t is the specimen thickness and R is the radius of the bend.

Then, an appropriate value for the maximum stress can be obtained from the stress-strain curve of the test material.

C-ring specimens are commonly used to determine the susceptibility to stress-corrosion cracking of alloys in different product forms. This test is particularly useful for testing tubing, rod, and bar in the short-transverse direction, as illustrated in Fig. 5. The specimens are typically bolt loaded to a constant strain or constant load per ASTM G 338. If the stresses in the outer layers of the apex of the C-rings are in the elastic region, the stresses can be accurately calculated:

$$D_f = D - \Delta$$
$$\Delta = \sigma d^2/4EtZ$$

where D is the outer diameter of the C-ring before stressing, D_f is the outer diameter of the stressed C-ring, σ is the elastic stress, Δ is the change of D at the desired stress, d is the mean diameter ($D - t$), t is the wall thickness, E is the elastic modulus, and Z is the correction factor for curved beam.

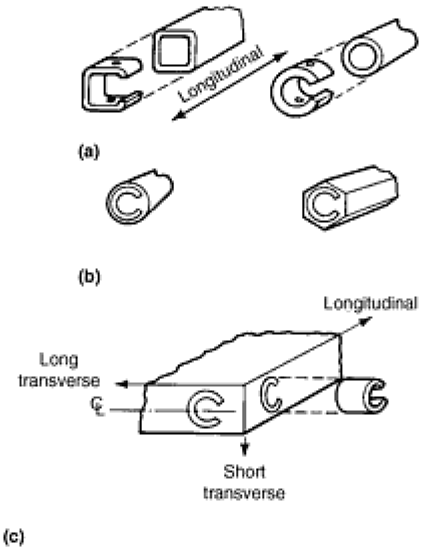

Fig. 5 Sampling procedure for testing various products with C-rings. (a) Tube. (b) Rod and bar. (c) Plate

The stress on C-ring specimens can be more accurately determined by attaching circumference and transverse strain gages to the stressed surface. The circumferential (σ_C), and transverse (σ_T) elastic stresses can be calculated:

$$\sigma_C = E(1 - \mu^2) \times (\varepsilon_C + \mu\varepsilon_T)$$
$$\sigma_T = E(1 - \mu^2) \times (\varepsilon_T + \mu\varepsilon_C)$$

where E is the elastic modulus, $\mu$is the Poisson's ratio, ε_C is the circumferential strain, and ε_T is the transverse strain.

Tensile Specimens. For specific purposes, such as alloy development, a large number of stress-corrosion specimens need to be evaluated. Tensile specimens have been used for this purpose where specimens used to determine tensile properties in air are adapted to SCC, as discussed in ASTM G 49. When uniaxially loaded in tension, the stress pattern is simple and uniform, and the magnitude of the applied stress can be accurately determined. Specimens can be quantitatively stressed by using equipment for application of either a constant load, a constant strain, or an increasing load or strain.

This type of test is one of the most versatile methods of SCC testing because of the flexibility permitted in the type and size of the test specimen, stressing procedures, and the range of stress level. It allows the simultaneous exposure of unstressed specimen (no applied load) with stressed specimens and subsequent tension testing to distinguish between the effects of true SCC and mechanical overload.

A wide range of test specimen sizes can be used, depending primarily on the dimensions of the product to be tested. Stress-corrosion test results can be significantly influenced by the cross section of the test specimen. Although large specimens may be more representative of most structures, they often cannot be prepared from the available product forms being evaluated. They also present more difficulties in stressing and handling in laboratory testing.

Smaller cross-sectional specimens are widely used. They have a greater sensitivity to SCC initiation, usually yield test results rapidly, and permit greater convenience in testing. However, the smaller specimens are more difficult to machine, and test results are more likely to be influenced by extraneous stress concentrations resulting from nonaxial loading, corrosion pits, and so on. Therefore, use of specimens less than about 10 mm (0.4 in.) in gage length and 3 mm (0.12 in.) in diameter is not recommended, except when testing wire specimens.

Tension specimens containing machined notches can be used to study SCC and hydrogen embrittlement. The presence of a notch induces a triaxial stress state at the root of the notch, in which the actual stress will be greater by a concentration factor that is dependent on the notch geometry. The advantages of such specimens include the localization of cracking to the notch region and acceleration of failure. However, unless directly related to practical service conditions, the results may not be relevant.

Tension specimens can be subjected to a wide range of stress levels associated with either elastic or plastic strain. Because the stress system is intended to be essentially uniaxial (except in the cast of notched specimens), great care must be exercised in the construction of stressing frames to prevent or minimize bending or torsional stresses.

The simplest method of providing a constant load consists of a dead weight hung on one end of the specimen. This method is particularly useful for wire specimens. For specimens of larger cross section, however, lever systems such as those used in creep-testing machines are more practical. The primary advantage of any dead-weight loading device is the constancy of the applied load.

Constant-strain SCC tests are performed in low-compliance tension-testing machines. The specimen is loaded to the required stress level, and the moving beam is then locked in position. Other laboratory stressing frames have been used, generally for testing specimens of smaller cross section.

Constant Load Testing

Although the constant extension tests are widely used for evaluating the susceptibility of alloys to SCC because of the ease of specimen preparation and the ability to test a large number of specimens at one time, there is one major drawback. Once stress-corrosion cracks have formed, the gross cross-sectional stress decreases, which will eventually cause the crack to stop. Application of a constant or a static load provides an alternative test method that represents some actual field conditions that can provide threshold values. It should be cautioned, however, that such threshold values are strongly dependent on the method of loading (i.e., dead weight or spring) and the specimen size and cannot be considered a materials property. Moreover, Fig. 6 shows that as a crack develops, the stress at the crack tip increases, possibly decreasing the time to failure.

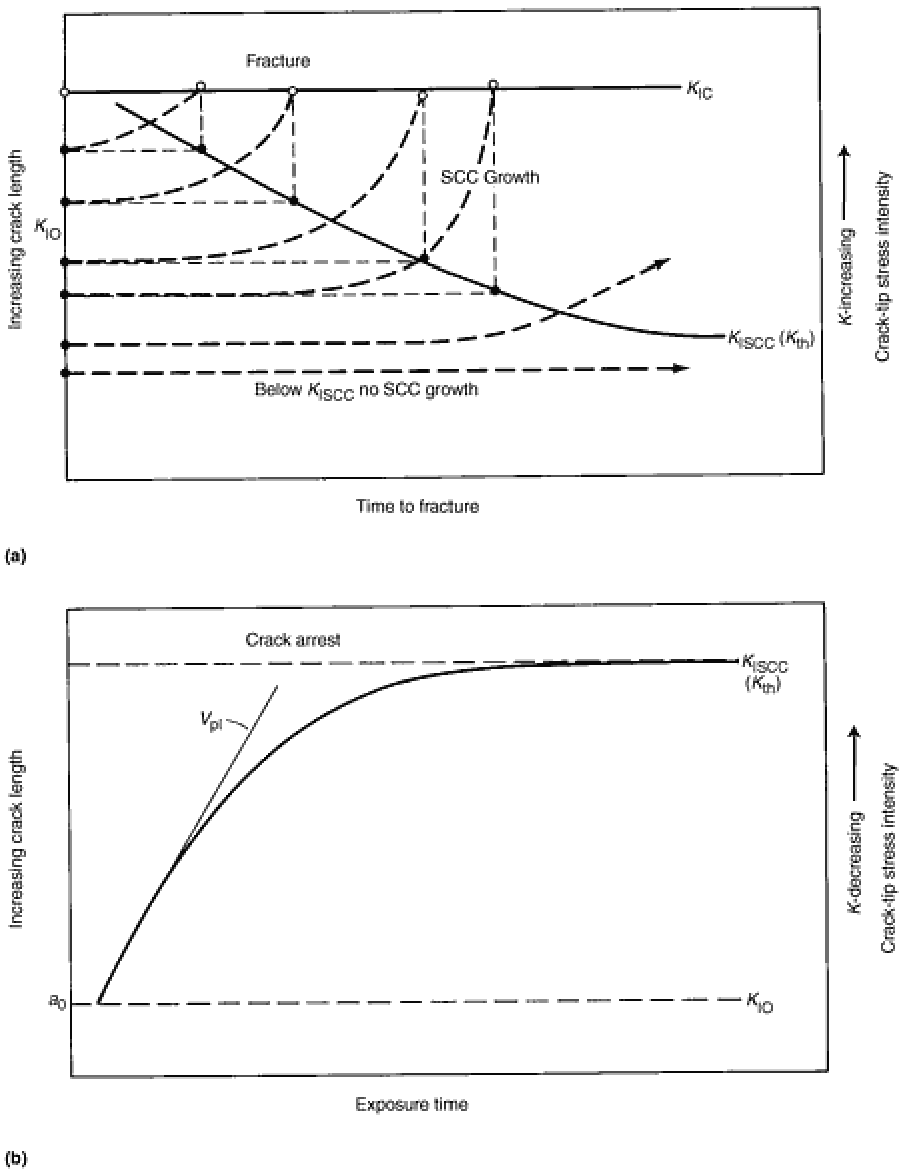
Fracture
K_{IC}
SCC Growth
Increasing crack length
K_{IO}
K_{ISCC} (K_{th})
Below K_{ISCC} no SCC growth
K-increasing
Crack-tip stress intensity
Time to fracture
(a)
Crack arrest
K_{ISCC}
(K_{th})
V_{pl}
Increasing crack length
a_0
K_{IO}
K-decreasing
Crack-tip stress intensity
Exposure time
(b)

Fig. 6 Schematic comparison of determination of threshold stress integrity factor (K_{ISCC} or K_{th}). (a) Constant-load (*K*-increasing) test. (b) Constant crack opening displacement (*K*-decreasing) test

Constant Strain-Rate Testing

Constant or slow strain-rate testing is a very useful technique to evaluate the susceptibility of materials to SCC in a relatively short period of time. Typical strain rates range between 10^{-5}/s and 10^{-7}/s, but for most materials the typical strain rate is at 10^{-6}/s. The strain sensitivity to SCC can change for different alloys, even of the same metal. Figure 7 shows that for the 2000-series aluminum alloys, the critical strain rate for the highest susceptibility to cracking is 10^{-6}/s, whereas no such critical strain rate exists for the 7000-series aluminum alloys. This difference in slow strain-rate behavior of the two alloys may indicate different mechanisms for SCC. The slow strain-rate behavior indicates that the principal mechanism for cracking of the 2000-series alloys is film rupture (anodic dissolution model), while the predominant mechanism for cracking of the 7000-series alloys is hydrogen embrittlement.

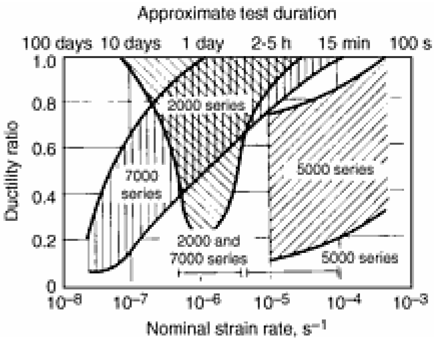

Fig. 7 Strain rate regimes for SCC of 2000, 5000, and 7000 series aluminum alloys in a 3% aqueous NaCl solution plus 0.3% H_2O_2

The parameters that are typically measured in slow strain-rate testing to determine the susceptibility to SCC are:

- Time to failure
- Percent elongation
- Percent reduction in cross-sectional area at the fracture surface
- Reduction in ultimate (UTS) and yield (YTS) tensile stress
- Presence of secondary cracking on the specimen gage section
- Appearance of the fracture surface

In order to assess the susceptibility of a material to SCC, the results of the slow strain-rate test in a particular environment must be compared with those in an inert environment, such as dry nitrogen gas.

Precracked Specimen Testing

The use of precracked specimens in the evaluation of SCC is based on the engineering concept that all structures contain cracklike flaws. Moreover, precracking can contribute to the susceptibility to SCC of alloys, such as titanium alloys, and this susceptibility may not always be evident from smooth specimens.

Precracking eliminates the uncertainties that are associated with crack nucleation and can provide a flaw geometry for which a stress analysis is available through fracture mechanics. Expressing stress-corrosion characteristics in terms of fracture mechanics provides a relationship between applied stress, crack length, and crack growth in a corrosive environment. When the plasticity can be ignored, or in other words, when the plastic zone ahead of the propagating crack is below a certain value and a triaxial or plane strain stress state exists at the crack tip, linear elastic fracture mechanics (LEFM) can be applied to describe the relationship between crack length (a) and the applied stress (σ) by stress intensity factor K:

$$K = \sigma \sqrt{a} \cdot F$$

where F is a polynomial factor that accounts for the specimen geometry. Linear elastic fracture mechanics, and thus K-factor, cannot be used to describe the relationship between applied stress and the crack length when there is significant plasticity or when the stress state at the crack tip is biaxial or plane stress. Then, a more fundamental parameter, the J-integral, is used.

Almost all standard plane-strain fracture mechanics test specimens can be adapted to SCC testing. Several examples are shown schematically in Fig. 8. ASTM Standard E 399 describes the allowable specimen dimensions and test procedures for precracked specimens.

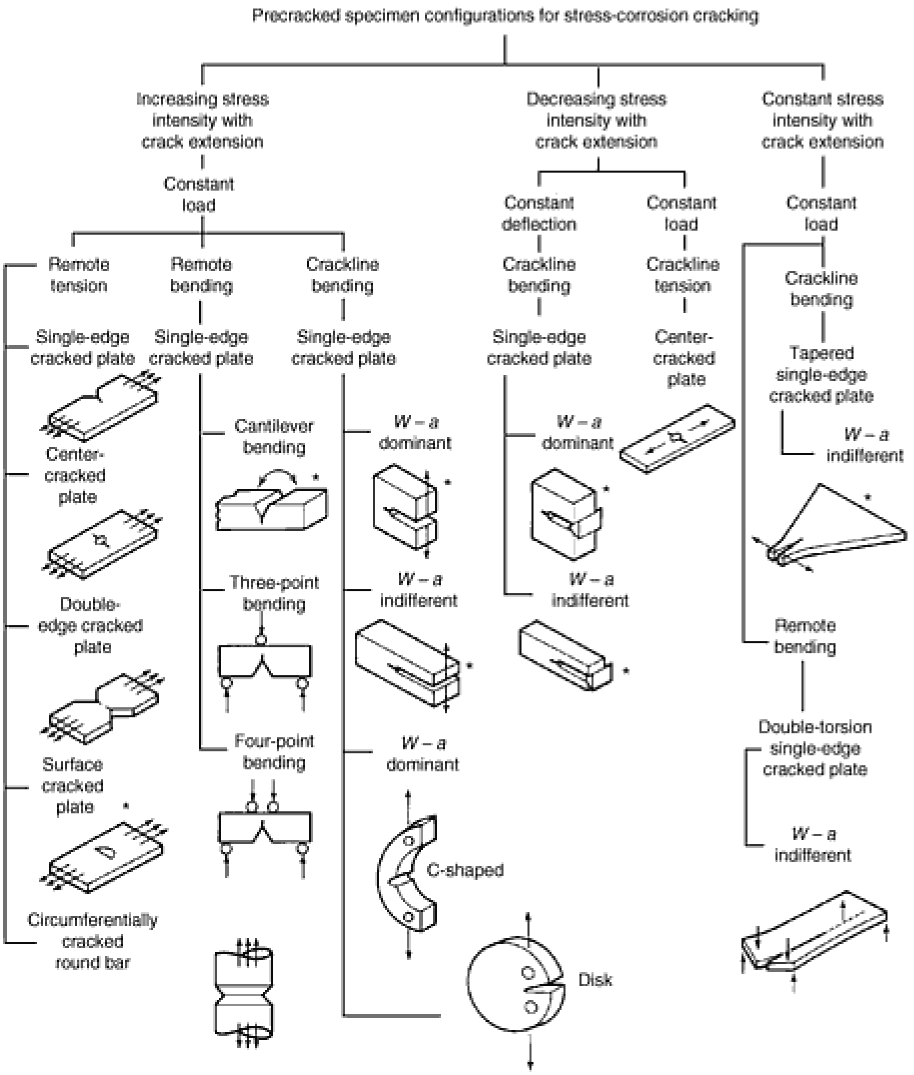
Precracked specimen configurations for stress-corrosion cracking
Increasing stress intensity with crack extension
Constant load
Remote tension
Remote bending
Crackline bending
Single-edge cracked plate
Single-edge cracked plate
Single-edge cracked plate
Center-cracked plate
Double-edge cracked plate
Surface cracked plate
*
Circumferentially cracked round bar
Cantilever bending
*
Three-point bending
Four-point bending
W – a dominant
*
W – a indifferent
*
W – a dominant
C-shaped
Disk
Decreasing stress intensity with crack extension
Constant deflection
Constant load
Crackline bending
Crackline tension
Single-edge cracked plate
Center-cracked plate
W – a dominant
*
W – a indifferent
*
Constant stress intensity with crack extension
Constant load
Crackline bending
Tapered single-edge cracked plate
W – a indifferent
*
Remote bending
Double-torsion single-edge cracked plate
W – a indifferent

Fig. 8 Classification of precracked specimens for SCC testing

Specimen Preparation. When using precracked fracture mechanics specimens, specific dimensional requirements need to be considered, as well as crack configuration and orientation. The basic dimensional requirement for application of LEFM is that dimensions are such that plane-strain condition can be maintained. In general, for a valid K measurement, neither that crack length nor the specimen thickness should be less than 2.5 $(K_{Ic}/\sigma_Y)^2$.

Several designs of initial crack configuration are available. ASTM E 399 recommends that the notch root radius is not greater than 0.127 mm (0.005 in.) unless a chevron notch is used, in which case it may be 0.25 mm (0.01 in.). In order to start out with a crack as sharp as possible, ASTM E 399 describes procedures for precracking. The K-level used for precracking should not exceed about two-thirds of the intended initial K-value. This procedure prevents the forming of compressive stresses at the crack tip, which may alter the SCC behavior of the alloys.

Aluminum alloys can also be precracked by the pop-in method, where the wedge-opening method is used to the point of tensile overload. This method cannot be used for steels and titanium alloys, because of their strength.

Loading Procedures. Stress-corrosion crack growth in precracked specimens can be studied in K-increasing and K-decreasing tests. In constant load or K-increasing test, crack growth results in increased crack opening, which keeps the environment at the crack tip and corrosion products from interfering with crack growth. One of the problems with this mode of loading is that with increasing K, the plastic zone ahead of the crack tip may increase and at some point interfere with crack propagation. Moreover, for this type of testing, bulky and relatively expensive equipment is required.

Constant displacement (K-decreasing) tests do not have the problems of the K-increasing tests. The plastic zone ahead of the crack tip does not increase with increasing crack size, so that the stress condition always remains in the plane-strain mode. Also, the constant displacement tests can be self-loaded, and thus external testing equipment is not needed. Because in these tests the stress-intensity factor, K_{ISCC}, can be easily determined by exposing a number of specimens loaded to different initial K_I values. This can even be accomplished by crack arrest in one specimen.

A major problem with this test method occurs when corrosion products form in the crack, blocking the crack mouth and interfering with the environment at this crack tip. Moreover, the oxide can wedge open the crack and change the originally applied displacement and load.

Measurement of Crack Growth. In order to quantify the crack growth behavior in precracked stress-corosion specimens, the crack length needs to be monitored, so that the crack velocity (da/dt) can be calculated, and the relationship between the increasing K and the crack velocity can be determined. There are basically three methods to monitor the growth of stress-corrosion cracks: visual/optical measurements, measurement of the crack-opening displacement using clip gages, and the potential drop measurement, which monitors the increase in resistance across two on either side of the propagating crack.

Tests for Hydrogen Embrittlement

HYDROGEN EMBRITTLEMENT is a time-dependent fracture process caused by the absorption and diffusion of atomic hydrogen into a metal, which results in a loss in ductility and tensile strength. Hydrogen embrittlement is distinguished from stress-corrosion cracking generally by the interactions of the specimens with applied currents. Cases where the applied current makes the specimen more anodic and accelerates cracking are considered to be stress-corrosion cracking, with the anodic-dissolution process contributing to the progress of cracking. On the other hand, cases where cracking is accentuated by current in the opposite direction, which accelerates the hydrogen-evolution reaction, are considered to be hydrogen embrittlement.

Tests for hydrogen embrittlement are performed to determine the effect of hydrogen damage in combination with residual or applied stresses. In the past decade, conventional testing methods have been modified to incorporate fracture mechanics, and the various types of hydrogen damage have been classified further in terms of crack nucleation, crack growth rates, and threshold stress-intensity measurements.

Testing Methods

As described in the section "Tests for Stress-Corrosion Cracking" in this article, the cantilever beam test and the wedge-opening load test result in a parameter called K_{ISCC}, which is the threshold stress intensity for SCC. Many different designations, such as K_{th}, K_{IHE}, and K_{SH}, denote this parameter for steels that undergo a similar phenomenon in which the mechanism is internal hydrogen embrittlement.

The threshold stress intensity for hydrogen stress cracking is designated by K_{IHE}, and K_{ISCC} is used for SCC. The mechanisms are different in that SCC occurs under anodic polarization conditions, whereas hydrogen embrittlement and hydrogen stress cracking occur under cathodic polarization conditions, which normally are generated to protect steels from corrosion. Such is the case when a sacrificial anode is galvanically coupled to the steel hull of a ship to prevent the hull from corroding. In such a couple, the steel is the cathode and hydrogen is produced at the cathode in an electrochemical reaction. This results in a steel structure, apparently free of corrosion (with a clean, metallic luster), that fails by intergranular cracking due to internal diffusion of hydrogen generated at the surface. This type of hydrogen embrittlement is found in types 410 and 17-4PH stainless steel and AISI type 4340 steel.

The cantilever beam test is a constant-load test in which a V-notched specimen is inserted along a portion of the beam and enclosed by an environmental chamber (Fig. 9). A crack at the root of the V-notch is initiated and extended by fatigue before testing. Notch-root thickness is prescribed by ASTM, although the requirement often is excessive for high-toughness steels. The specimen is subjected to a constant load over a preset time period. As the crack grows, the stress intensity increases. Time to time failure is plotted versus applied stress intensity. The lower limit of the resultant curve is a threshold for hydrogen embrittlement (Fig. 10).

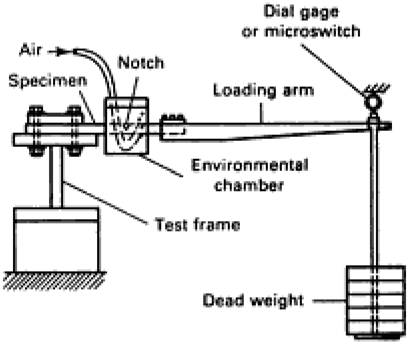

Fig. 9 Fatigue-cracked cantilever beam test specimen and fixtures

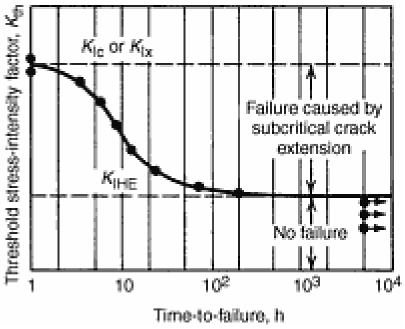

Fig. 10 Procedure to obtain K_{IHE} with precracked cantilever beam test specimen

The K_{IHE} results of a cantilever beam test depend on how much time elapses before the test is terminated. Recommended testing periods to establish the true stress-intensity threshold vary, ranging from 200 h, which is typical for hydrogen embrittlement testing, to as long as 5000 h. Another limitation of this testing method is that it can be expensive in terms of materials and machining. As many as 12 specimens, placed under different loads in separate test machines, are needed per test to obtain valid K_{IHE} values.

The wedge-opening load test applies a constant wedge or crack opening displacement; as the crack extends, stress intensity decreases until crack arrest occurs (Fig. 11). The initial load is assumed to be slightly above K_{IHE}. The specimen is maintained under these conditions for about 5000 h to establish the threshold. The crack grows to a point after which further growth is not measured (K_{IHE}). However, it is difficult to determine precisely when the "no growth" criterion is met. Crack tip opening displacement should also be monitored. Corrosion reactions accompanied by expansion in volume may occur at the crack tip. This changes the opening displacement and increases the load, thus altering desired testing conditions.

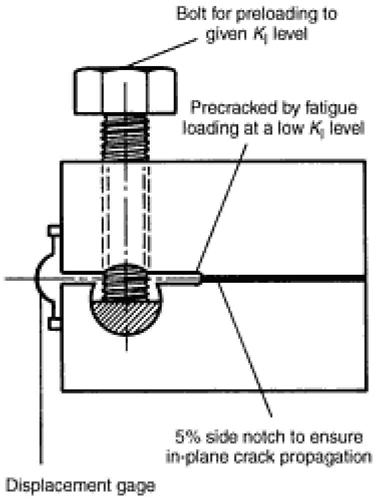
Bolt for preloading to given K_I level
Precracked by fatigue loading at a low K_I level
5% side notch to ensure in-plane crack propagation
Displacement gage

Fig. 11 Schematic showing basic principle of modified wedge-opening load test specimen

As subcritical crack extension occurs, stress intensity increases in the cantilever beam test and decreases in the wedge-opening load test (Fig. 12). Generally, the threshold stress intensity measured with the wedge-opening load test is lower than with the cantilever beam test. The advantage of the wedge-opening load test is that only a single specimen is required to measure K_{IHE}.

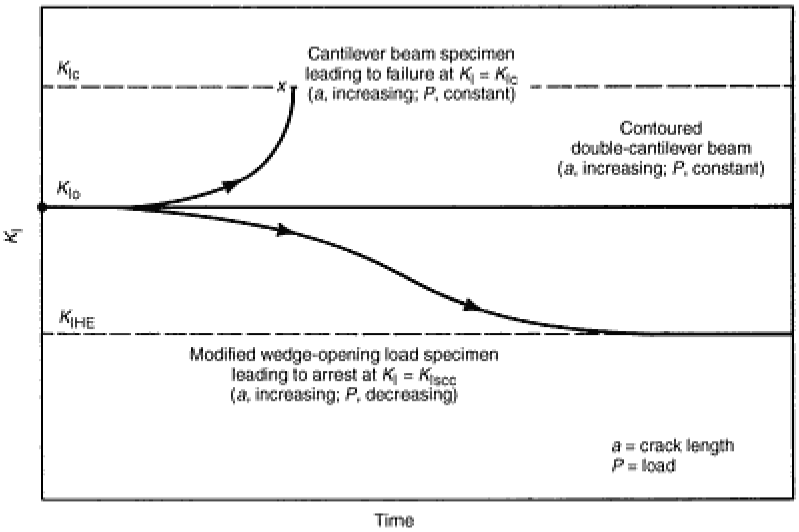

Fig. 12 Influence of time, crack extension, and load on stress-intensity behavior of modified wedge-opening load, cantilever beam, and contoured double-cantilever beam test specimens

The contoured double-cantilever beam test is used to measure crack growth rate a constant stress-intensity factor. This test simplifies the calculation of stress intensity by using a contoured specimen so that stress intensity is proportional to the applied load and is independent of the crack length. Under a constant load, stress intensity also remains constant with crack extension. For the test geometry shown in Fig. 13, the stress-intensity factor equals 20 times the load ($K = 20P$).

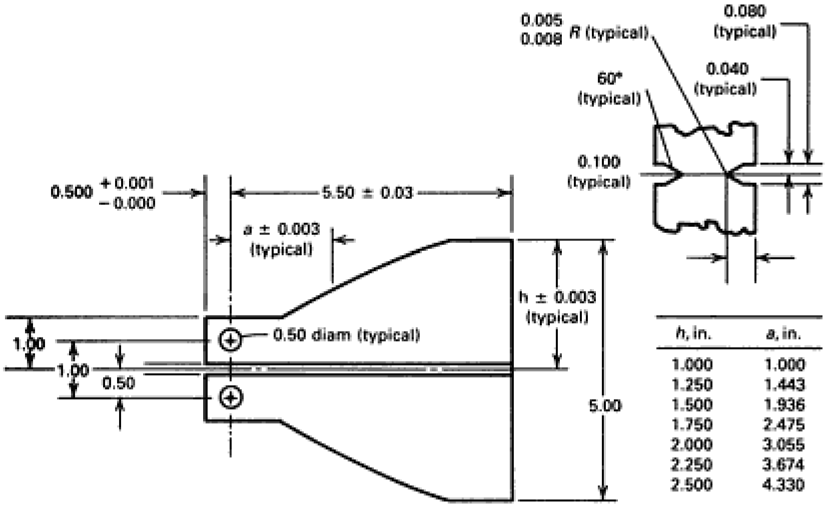
0.005
0.008 R (typical)
0.080
(typical)
60°
(typical)
0.040
(typical)
0.100
(typical)
0.500 +0.001 −0.000
5.50 ± 0.03
a ± 0.003
(typical)
h ± 0.003
(typical)
1.00
1.00
0.50
0.50 diam (typical)
5.00
h, in.
a, in.
1.000 1.000
1.250 1.443
1.500 1.936
1.750 2.475
2.000 3.055
2.250 3.674
2.500 4.330

Fig. 13 Dimensions and configuration for double-cantilever beam test specimen. Specimen contoured to $3a^2/h^3 + 1/h = C$, where C is a constant. All values given in inches (1.0 in. = 25.4 mm).

Data on hydrogen embrittlement can be obtained with subthickness specimens, even in excess of the ASTM requirement of $K^2_{\max} < 0.4\ B/(\mathrm{YS})^2$ (where B is thickness and YS is yield strength of the specimen), by using side grooves, which provide additional constraint on the material being tested. Side grooves enable the maintenance of a plane-strain condition in a thin specimen by enhancing stress triaxiality. This method has been used extensively to study the effect of heat treatment (hardness) and environment on hydrogen stress cracking of AISI type 4340 steels (Fig. 14).

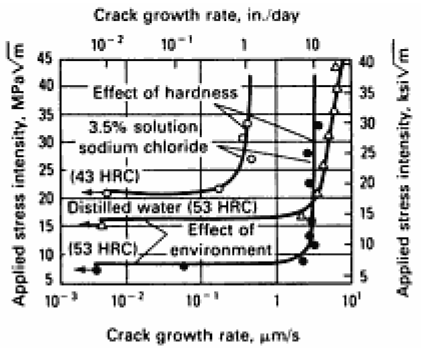

Fig. 14 Hydrogen embrittlement crack growth rate as a function of applied stress intensity for two different hardnesses and environments for an AISI 4340 steel contoured double-cantilever beam test specimen

The contoured double-cantilever beam test has also been used to study the stress-history effect that produces an incubation time before hydrogen stress cracking. Figure 15 shows that incubation time is dependent on the type of steel. A decrease in the stress-intensity factor from 44 to 22 MPa$\sqrt{\mathrm{m}}$ (40 to 20 ksi$\sqrt{\mathrm{in.}}$) may change the incubation time from less than 1 h for AISI type 4340 steel to about 1 year for type D-6AC steel.

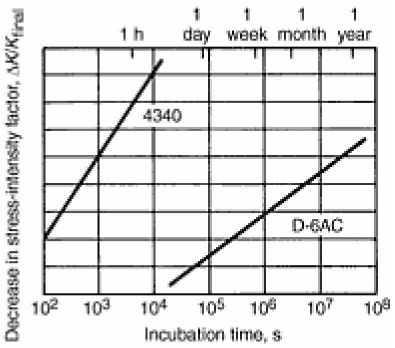

Fig. 15 Incubation time prior to hydrogen stress cracking for AISI type 4340 and type D-6AC steel contoured double-cantilever beam test specimens as a function of decrease in stress intensity

Three-Point and Four-Point Bend Tests. The contoured double-cantilever beam test uses a constant load to maintain a constant stress-intensity factor with crack extension. The same effect can be produced by using a three- or four-point bend test under displacement control. These tests use heavily side-grooved Charpy V-notch specimens (Fig. 16). Because crack opening displacement is constant as the crack extends, the load decreases, so that there is a slight initial increase in stress intensity to a maximum value that drops slightly as the ratio of crack depth to specimen width exceeds 0.5. Typically, stress intensity is constant, within a small range. Figure 17 compares the change in stress-intensity factor with crack extension as a function of load control to that of displacement control for a three-point bend specimen.

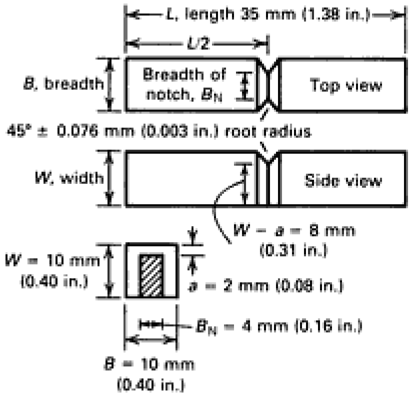
L, length 35 mm (1.38 in.)
L/2
B, breadth
Breadth of notch, B_N
Top view
45° ± 0.076 mm (0.003 in.) root radius
W, width
Side view
W − a = 8 mm (0.31 in.)
W = 10 mm (0.40 in.)
a = 2 mm (0.08 in.)
B_N = 4 mm (0.16 in.)
B = 10 mm (0.40 in.)

Fig. 16 Standard side-grooved Charpy V-notch test specimen used for three- and four-point bend tests

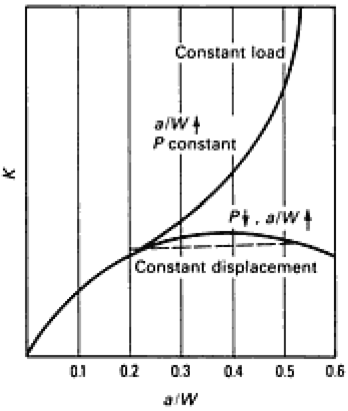

Fig. 17 Use of three-point bend displacement control as constant-*K* specimen

The rising step-load test provides a stress intensity that is different at each load but remains constant with crack extension as each load level is sustained. Crack initiation is signaled by a drop in load (Fig. 18). The rising step-load test was developed as an accelerated low-cost test to measure resistance of steels (particularly weldments) to hydrogen embrittlement. The threshold obtained by this method will be somewhat high, as test duration at each load is short.

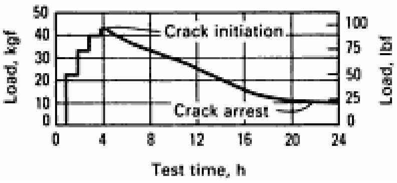

Fig. 18 Typical load-time record for four-point rising step-load test

To index susceptibility to hydrogen-assisted cracking, the test should last no longer than 24 h, and the hydrogen source should reflect the most aggressive environment. In one experiment, a 3.5% sodium chloride solution was selected to simulate seawater, and a cathodic potential of -1.2 V (saturated calomel electrode) was used to generate hydrogen to reproduce the extreme conditions of sacrificial anodic protection generally found on a ship hull.

A Charpy specimen was chosen, because such specimens are small and easy to machine and handle. In this test, however, the specimen was modified. Instead of using a fatigue precrack, the notch-root radius was machined to less than 7.6 μm (3 mil). This was done to lower the cost and give less ambiguous environmental conditions at the crack tip. Also, hydrogen cracks nucleate below the surface.

The specimen was deeply side grooved, a common practice used in hydrogen stress cracking tests to prevent the crack from branching. Side grooves are also used in crack opening displacement or *J*-integral testing to cause load-displacement curves to increase monotonically to fracture by inducing a highly triaxial stress field at the crack tip. Because a Charpy specimen is small, deep side grooves produce a triaxial stress field at the notch to promote hydrogen stress cracking. The extent of the side grooving is such that the remaining ligament is only 40% of the original thickness. The modified Charpy specimen dimensions are shown in Fig. 16.

The specimen was loaded by means of beams and an instrumented bolt (Fig. 19). Four-point bending under constant displacement control and stress intensity produced crack growth. Once cracking initiated at the notch ($a/W = 0.2$, where a is crack length and W is width of the specimen), arrest did not occur until the crack was nearly through the specimen. The load was increased manually at 1 h intervals. An environmental chamber encompassed the specimen and included a potentiostat to produce hydrogen while under stress.

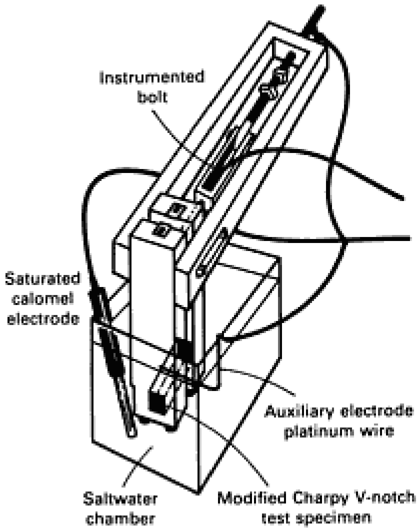
Instrumented bolt
Saturated calomel electrode
Auxiliary electrode platinum wire
Saltwater chamber
Modified Charpy V-notch test specimen

Fig. 19 Loading frame used for rising step-load test

The rising step-load test was used to evaluate high-strength HY ship steels and weldments in an environment simulating seawater under conditions of cathodic protection commonly used to protect ship hulls. Samples from the heat-affected zone and other locations in the weld metal were tested. Interlayer gas tungsten arc heating was evaluated as a means of providing a refined, homogeneous, tempered microstructure with improved resistance to hydrogen stress cracking. As a baseline, comparison was made between HY-130 and HY-180 steels.

Figure 20 plots rising step-load test results for HY-130 and HY-180 base metals, in addition to combinations of modified HY steel compositions and programmed-cooling-rate thermal cycles for the base metal and weld wire. The vertical axis is a plot of a parameter derived from the specimen strength ratio in ASTM E 399, "Test Method for Plane-Strain Fracture Toughness of Metallic Materials"--i.e., $6 P_{max}/B(W - a)^2\text{YS}$, where P_{max} is the maximum load that the specimen is able to sustain, B is the specimen thickness, W is the specimen width, a is the crack length, and YS is the yield strength in tension. For the data shown in Fig. 13, P_{max} was replaced by the crack initiation load. The horizontal axis is a ratio of K_{IHE}/YS, measured in a separate test program with cantilever beam and wedge-opening load specimens.

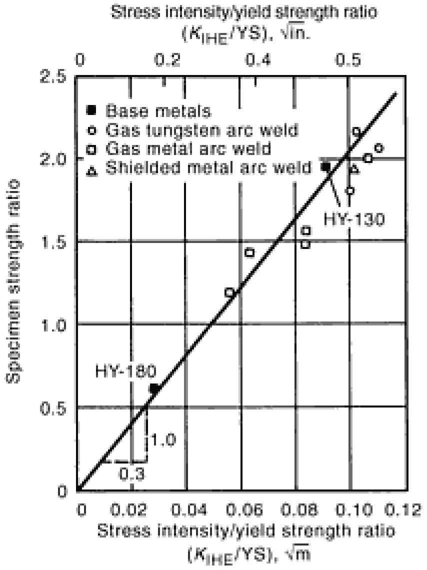

Fig. 20 Analytical correlation of strength ratio with threshold stress-intensity data

The resistance to hydrogen embrittlement of the two base metals and six locations in HY-130 weldments was ranked using this testing method. Test results showed that HY-180 is more susceptible to hydrogen stress cracking than HY-130 and that the resistance to hydrogen embrittlement of specimens taken from the heat-affected zone and fusion line is consistently higher than that of weld-metal specimens. The resistance of the weld metal is affected by the grain structure; interlayer gas tungsten arc reheating homogenized the weld structure, but did not temper the weld metal. Specimens from the gas tungsten arc reheated weldment consistently exhibited higher hardness and lower resistance to hydrogen embrittlement than similar specimens from the standard HY-130 weld metal.

The disk-pressure testing method measures susceptibility to hydrogen embrittlement of metallic materials under a high-pressure gaseous environment. The test is used for the selection and quality control of materials, protective coatings, surface finishes, and other processing variables.

A thin disk of the metallic materials to be tested is placed as a membrane in a test cell and subjected to helium pressure until the bursts. Because helium is inert, the fracture is caused by mechanical overload; no secondary physical or chemical action is involved. An identical disk is placed in the same test cell and subjected to hydrogen pressure until it bursts. Metallic materials that are susceptible to environmental hydrogen embrittlement fracture under a pressure lower than the helium-burst pressure; materials that are not susceptible fracture under the same pressure for both hydrogen and helium. The ratio (S_{H_2}) between the helium-burst pressure (P_{He}) and the hydrogen-burst pressure (P_{H_2}) indicates the susceptibility of the material to environmental hydrogen embrittlement:

$$S_{H_2} = \frac{P_{He}}{P_{H_2}}$$

If S_{H_2} is equal to or less than 1, the material is not susceptible to environmental hydrogen embrittlement. When S_{H_2} is greater than 2, the material is considered to be highly susceptible. At values between 1 and 2, the material is moderately susceptible, with failure expected after long exposure to hydrogen; therefore, the material must be protected against exposure.

Slow strain-rate tensile test can be used to evaluate many product forms, including plate, rod, wire, sheet, and tubing, as well as welded parts. Smooth, notched, or precracked specimens can be used. The principal advantage of this standardized test is that the susceptibility to hydrogen stress cracking for a particular metal-environment combination can be assessed rapidly.

A variety of specimen shapes and sizes can be used; the most common is a smooth bar tensile coupon, as described in ASTM E 8, "Methods of Tension Testing of Metallic Materials." The specimen is exposed to the environment and is stressed under displacement control. For stainless steel in chloride solution, the strain rate is 10^{-6}s. One or more of the following parameters are applied to the tensile test at the same initial strain rate; time-to-failure; ductility, as assessed by reduction in area or elongation to fracture, for example; maximum load achieved; and area bounded by a nominal stress-elongation curve or a true stress-true strain curve.

Potentiostatic Slow Strain-rate Tensile Testing. The use of dissociated water under potentiostatic conditions that produce hydrogen on the surface of the tensile test specimen while under slow strain-rate displacement control has been studied. Results suggest that hydrogen is the most significant parameter in stress cracking under conditions of hydrogen sulfide stress-corrosion cracking found in oil fields.

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Metallographic Practices Generally Applicable to All Metals

Edited by George F. Vander Voort, Buehler Ltd.

Metallographic Methods

THE METHODS AND EQUIPMENT described in this article cover the preparation of specimens for examination by light optical microscopy (LOM), scanning electron microscopy (SEM), electron microprobe analysis (EMPA) for microindentation hardness testing, and for quantification of microstructural parameters, either manually or by the use of image analyzers.

In this article, it is assumed that the specimen or specimens being prepared are representative of the material to be examined. Random sampling, as advocated by statisticians, can rarely be performed by metallographers. Instead, systematically chosen test locations are employed based on convenience in sampling. In failure studies, specimens are usually removed to study the origin of the failure, to examine highly stressed areas, and to examine secondary cracks.

All sectioning processes produce damage; some methods (such as flame cutting) produce extreme amounts of damage. Traditional laboratory sectioning procedures using abrasive cut-off saws introduce minor damage that varies with the material being cut and its thermal and mechanical history. This damage must be removed if the true structure is to be examined. However, because abrasive grinding and polishing steps also produce damage, where the depth of damage decreases with decreasing abrasive size, the preparation sequence must be carefully planned and performed. Otherwise, preparation-induced artifacts will be interpreted as structural elements. A properly prepared specimen has the following characteristics:

- Deformation induced by sectioning, grinding, and polishing is removed or shallow enough to be removed by the etchant.
- Coarse grinding scratches are removed; fine polishing scratches are tolerated in routine metallographic studies.
- Pullout, pitting, cracking of hard particles, and smear are avoided.
- Relief (i.e., excessive surface height variations between structural features of different hardness) is minimized.
- The surface is flat particularly at edges (if they are to be examined) and at coated surfaces to permit examination at high magnifications.
- Specimens are cleaned adequately between preparation steps, after preparation, and after etching.

Preparation of metallographic specimens generally requires five major operations: sectioning, mounting (optional), grinding, polishing, and etching (optional).

Sectioning

Many metallographic studies require more than one specimen. For example, a study of deformation in wrought metals usually requires two sections--one perpendicular and the other parallel to the direction of deformation. A failed part may best be studied by selecting a specimen that intersects the origin of the failure, if the origin can be identified. Depending on the type of failure, it may be necessary to take several specimens from the area of failure and from adjacent areas.

Sampling. Bulk samples for sectioning may be removed from larger pieces or parts using methods such as core drilling, band or hack sawing, flame cutting, etc. However, when these techniques are used, precautions must be taken to avoid alteration of the microstructure in the area of interest. Laboratory abrasive-wheel cutting is recommended to establish the desired plan of polish. In the case of relatively brittle materials, sectioning may be accomplished by fracturing the specimen at the desired location.

Abrasive-Wheel Cutting. By far, the most widely used sectioning devices in metallographic laboratories are abrasive cut-off machines (Fig. 1). All abrasive-wheel sectioning should be done wet. An ample flow of water, with a water-soluble oil additive for corrosion protection, should be directed into the cut. Wet cutting will produce a smooth surface finish and, most importantly, will guard against excessive surface damage caused by overheating. Abrasive wheels should be selected according to the recommendations of the manufacturer. Specimens must be fixtured securely during cutting, and cutting pressure should be applied carefully to prevent wheel breakage.

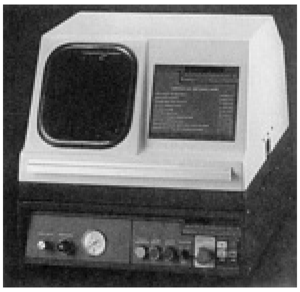


Fig. 1 A tabletop automated abrasive cutoff saw

Mounting of Specimens

The primary purpose of mounting metallographic specimens is for convenience in handling specimens of difficult shapes or sizes during the subsequent steps of metallographic preparation and examination. A secondary purpose is to protect and preserve extreme edges or surface defects during metallographic preparation. The method of mounting should in no way be injurious to the microstructure of the specimen. Mechanical deformation and heat are the most likely sources of injurious effects.

Clamp Mounting. Clamps have been used for mounting metallographic cross sections in the form of thin sheets. Several specimens can be clamped conveniently in sandwich form. This method is quick and convenient for mounting sheet type specimens; and when done properly, edge retention is excellent. There is no problem with seepage of fluids from crevices between specimens. The outer clamp edges must be beveled to minimize damage to polishing cloths. If clamps are improperly used so that gaps exist between specimens, fluids and abrasives can become entrapped and will seep out obscuring edges. The problems can be minimized by proper tightening of clamps, by use of plastic spacers between specimens, or by coating specimen surfaces with epoxy before tightening.

Compression Mounting. The most common mounting method uses pressure and heat to encapsulate the specimen with a thermosetting or thermoplastic mounting material. Common thermosetting resins include phenolic, such as Bakelite (Union Carbide Corp., Danbury, CT) and diallyl phthalate, while methyl methacrylate is the most common thermoplastic mounting resin. Both thermosetting and thermoplastic materials require heat and pressure during the molding cycle; but after curing, mounts made of thermoplastic resins must be cooled to ambient under pressure, while mounts made of thermosetting materials may be ejected from the mold at the maximum molding temperature. However, cooling thermosetting resins under pressure to at least 55 °C (130 °F) before ejection will reduce shrinkage gap formation. A thermosetting resin mount should never be water cooled after hot ejection from the molding temperature. Thermosetting epoxy resins provide the best edge retention of these resins and are less affected by hot etchants than phenolic resins. Mounting presses vary from simple laboratory jacks with a heater and mold assembly to full automated devices (Fig. 2).

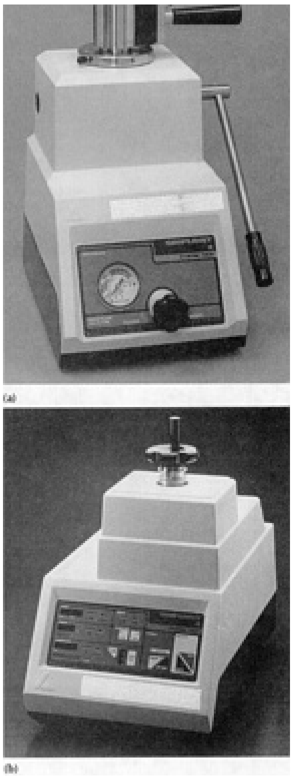


Fig. 2 Mounting presses vary from a simple laboratory manual device (a) to a fully automated press (b)

Cold mounting materials require neither pressure nor external heat and are recommended for mounting specimens that are sensitive to heat and/or pressure. Acrylic resins are the most widely used castable resin due to their low cost and fast curing time; however, shrinkage is somewhat of a problem. Epoxy resins, although more expensive than acrylics, are commonly used because epoxy will physically adhere to specimens and can be drawn into cracks and pores, particularly if a vacuum impregnation chamber is employed. Hence, epoxies are very suitable for mounting fragile or friable specimens and corroded or oxidized specimens. Dyes or fluorescent agents are added to some epoxies for the study of porous specimens, such as thermal spray coated specimens. Most epoxies are cured at room temperature, and curing times can be as long as 6 to 12 h. Some epoxies can be cured at slightly elevated temperatures in less time. Hard filler particles have been added to epoxy mounts for edge retention, but this addition is really not a satisfactory solution.

Taper sectioning (mounting) generally is regarded as a special mounting technique; it enables the metallographer to examine in greater detail the immediate subsurface structure or surface topography of a specimen. Microhardness determinations and thickness measurements of thin surface coatings or diffusion zones may be performed on taper-sectioned specimens. Taper sectioning (Fig. 3) is accomplished by establishing a plane of polish at a small angle to the surface of the specimen.

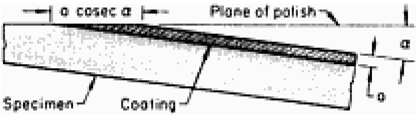


Fig. 3 Schematic of taper sectioning (mounting), as applied to a coated specimen. Taper magnification equals the cosecant of taper angle, α.

Edge preservation is a long-standing metallographic problem and many "tricks" have been promoted (most pertaining to mounting, but some to grinding and polishing). These methods include the use of backup material in the mount, the application of coatings to the surfaces before mounting, and the addition of a filler material to the mount. Plating of a compatible metal on the surface to be protected (electroless nickel has been widely used) is generally considered to be the most effective procedure.

However, introduction of new technology has greatly reduced edge preservation problems. First, use of mounting presses, which cool the specimen to near ambient temperature under pressure, produces much tighter mounts. Gaps that form between specimen and resin are a major contributor to edge rounding. Second, use of semi-automatic and automatic grinding/polishing equipment, rather than manual (hand) preparation, increases surface flatness and edge retention. Third, the use of harder, woven or nonwoven, napless surfaces for polishing with diamond abrasives, rather than softer cloths, such as canvas, billiard, and felt, maintains flatness. Final polishing using low-nap cloths for short times introduces very little rounding compared to use of higher nap, softer cloths.

Grinding

Grinding should commence with the finest grit size that will establish an initially flat surface and remove the effects of sectioning within a few minutes. An abrasive grit size of 180 or 240 grit is coarse enough to use on specimen surfaces sectioned by an abrasive cut-off wheel. Hack-sawed, band-sawed, or other rough surfaces usually require abrasive grit sizes from 120 to 180 grit. The abrasive used for each succeeding grinding operation should be one or two grit sizes smaller than that used in the preceding operation. A satisfactory fine grinding sequence might involve grit sizes of 240, 320, 400, and 600 grit. This sequence is known as the "traditional" approach.

As in abrasive-wheel sectioning, all grinding should be done wet provided that water has no adverse effects on any constituents of the microstructure. Wet grinding minimizes loading of the abrasive with metal removed from the specimen being prepared and minimizes specimen heating.

Each grinding step, while producing damage itself, must remove the damage from the previous step. The depth of damage decreases with the abrasive size but so does the metal removal rate. For a given abrasive size, the depth of damage introduced is greater for soft materials than for hard materials.

Besides SiC paper, a number of other options are available to circumvent their use. One option, used chiefly with semi-automatic and automatic systems, is to grind a number of specimens placed in a holder simultaneously using a conventional grinding stone generally made of coarse grit alumina. This step, often called "planar grinding," has the second goal of making all of the specimen surfaces coplanar. This process requires a special-purpose machine because the stone must rotate at a high speed, $\geq$1500 rpm, to cut effectively. The stone must be dressed regularly with a diamond tool to maintain flatness.

Other materials have also been used both for the planar grinding stage or, afterwards, to replace SiC paper. For very hard materials such as ceramics and sintered carbides, two or more metal-bonded or resin-bonded diamond disks with grit sizes from about 70 to 9 μm can be used. An alternate type of disk has diamond particles suspended in a resin applied in small blobs, or spots, to a disk surface. These disks are available with diamond sizes from 120 to 6 μm. Another type of disk available in several diamond sizes uses diamond attached to the edges of a perforated, screen-like metal disk. Another approach uses a stainless steel woven mesh "cloth" on a platen charged with coarse diamond, usually in slurry form, for planar grinding. Once planar surfaces have been obtained, there are several single-step procedures available for avoiding the finer SiC papers. These processes include the use of platens, woven polyester thick cloths, or rigid grinding disks. With each of these, a coarse diamond size, most commonly 9 μm, is used.

Grinding Media. The grinding abrasives commonly used in the preparation of metallographic specimens are silicon carbide (SiC), aluminum oxide (Al_2O_3), emery (Al_2O_3-Fe_3O_4), composite ceramics, and diamond. All except diamond are generally bonded to paper or cloth-backing materials of various weights in the form of sheets, disks, and belts of various sizes. Limited use is made of grinding wheels consisting of abrasives embedded in a bonding material. The abrasives may be used also in powder form by charging the grinding surfaces with loose abrasive particles or with abrasive in a premixed slurry or suspension.

Grinding Equipment. Although it is rarely used in industry, students still use stationary grinding paper that is supplied in strips or rolls (Fig. 4). The specimen is slid against the paper from top to bottom. Grinding in one direction is usually safer than grinding in both directions. While this can be done dry for certain delicate materials, water is usually added to keep the specimen surface cool and to carry the swarf away.

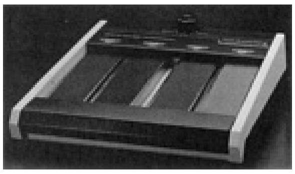


Fig. 4 A simple stationary grinding apparatus

Belt grinders (Fig. 5) are usually present in most laboratories. They are mainly used to remove burrs from sectioning, to round edges that need not be preserved for examination, to flatten cut surfaces to be macroetched, or to remove sectioning damage. Generally only very coarse abrasive papers grits from 60 to 240 grits are used. Most grinding work is done on rotating wheels; that is, a motor-driven platen upon which the SiC paper is attached (Fig. 6).

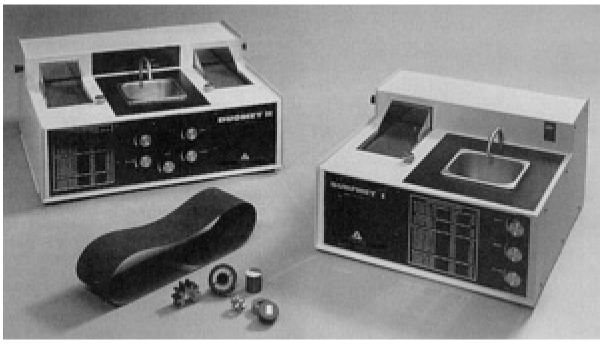


Fig. 5 Single and dual belt grinders for rough grinding

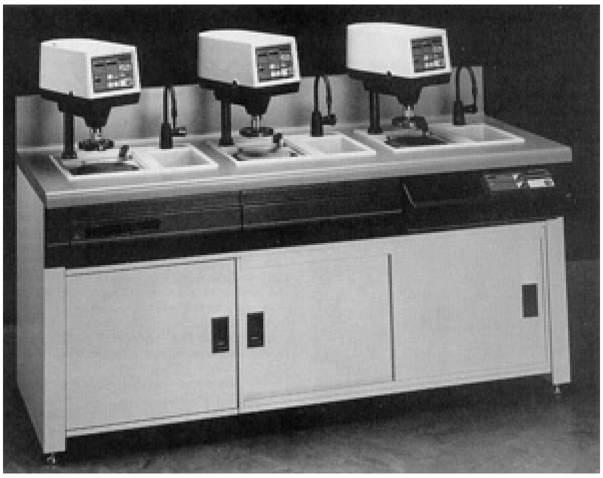


Fig. 6 Laboratory flush mounted semi-automatic grinder/polisher system

Lapping is an abrasive technique in which the abrasive particles roll freely on the surface of a carrier disk. During the lapping process, the disk is charged with small amounts of a hard abrasive, such as diamond or silicon carbide. Lapping disks can be made of many different materials; cast iron and plastic are used most commonly. Lapping produces a flatter specimen surface than grinding, but it does not remove metal as in grinding. Consequently, lapping is not commonly employed in metallography. Some platens, referred to as laps, are charged with diamond slurries. Initially, the diamond particles roll over the lap surface (just as with other grinding surfaces), but they soon become embedded and cut the surface, producing chips.

Polishing

Polishing is the final step in producing a deformation-free surface that is flat, scratch-free, and mirror-like in appearance. Such a surface is necessary for subsequent metallographic interpretation, both qualitative and quantitative. The polishing technique used should not introduce extraneous structures, such as disturbed metal, pitting, dragging out of inclusion, "comet tailing," and staining. Polishing usually is conducted in several stages. Rough polishing generally is traditionally done with 6 or 3 μm diamond abrasive charged onto napless or low-nap cloths. Hard materials, such as through-hardened steels, ceramics, and cemented carbides, may require an additional polishing step. For such materials, initial rough polishing may be followed by polishing with 1 μm diamond on a napless, low-nap, or medium-nap cloth. A compatible lubricant should be used sparingly to prevent overheating or deformation of the surface. Intermediate polishing should be performed thoroughly so that final polishing may be of minimal duration. Manual, or "hand," polishing is usually conducted using a rotating "wheel" (Fig. 7).

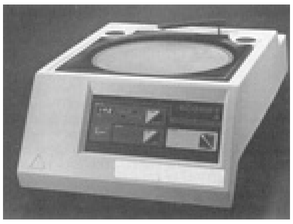


Fig. 7 Manual "hand" polishing setup

Mechanical Polishing

The term *mechanical polishing* is frequently used to describe the various polishing procedures involving the use of fine abrasives on cloth. The cloth may be attached to a rotating wheel or a vibrating bowl (Fig. 8). The specimens are held by hand, held mechanically, or merely confined within the polishing area.

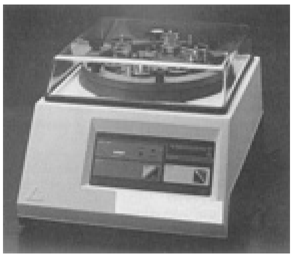


Fig. 8 Vibratory polishing unit

Hand Polishing. Aside from the use of improved polishing cloths and abrasives, hand-polishing techniques still follow the basic practice established many years ago:

- *Specimen Movement.* The specimen is held with one or both hands, depending on the operator's preference, and is rotated in a direction counter to the rotation of the polishing wheel. In addition, the specimen is continuously moved back and forth between the center and the edge of the wheel, thereby ensuring even distribution of the abrasive and uniform wear of the polishing cloth. Some metallographers use a small wrist rotation while moving the specimen from the center to the edge of one side of the wheel. The main reason for rotating the specimen is to prevent formation of "comet tails." This polishing artifact (Fig. 9) is a result of directional polishing of materials containing inclusions, fine precipitates, voids, or other similar features.
- *Polishing Pressure.* The correct amount of applied pressure must be determined by experience. In general, firm hand pressure is applied to the specimen in the initial movement.

- *Washing and Drying.* The specimen is washed and swabbed in warm running water, rinsed with ethanol, and dried in a stream of warm air. Scrubbing with cotton soaked with an aqueous soap solution followed by rinsing with water is also commonly employed. Alcohol usually can be used for washing when the abrasive carrier is not soluble in water or if the specimen cannot tolerate water.
- *Cleanness.* The precautions for cleanness, as previously mentioned, must be strictly observed.

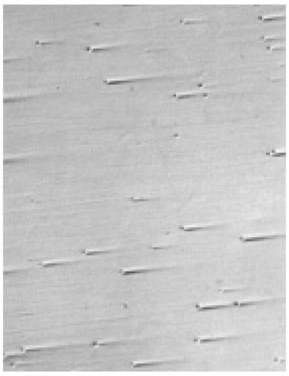


Fig. 9 "Comet tails" due to directional polishing and pull out of hard particles. 200×

For routine metallographic work, a fine diamond abrasive (1 μm) may be used as the last step. Traditionally, aqueous fine alumina slurries have been used for final polishing with medium-nap cloths. Alpha alumina (0.3 μm) and gamma alumina (0.05 μm) slurries (or suspensions) are popular for final polishing, either in sequence or singularly. Colloidal silica (basic pH about 9.5) and acidic alumina suspensions are newer final polishing abrasives being used for difficult to prepare materials. Vibratory polishers (Fig. 8) are often used for final polishing, particularly with more difficult to prepare materials, for image analysis studies, or for publication-quality work.

Automatic Polishing. Mechanical polishing can be automated to a high degree using a wide variety of devices ranging from relatively simple systems to rather sophisticated minicomputer- or microprocessor-controlled devices (Fig. 10). Units also vary in capacity from a single specimen (Fig. 11) to a half dozen or more at a time (Fig. 12). Most units can be used for all grinding and polishing steps. These devices enable the operator to prepare a large number of specimens per day, often with a higher degree of quality than that of hand polishing and at reduced consumable costs. Automatic polishing devices also are desirable for preparing radioactive specimens by remote control or for using corrosive-attack polishing procedures safely without hand contact.

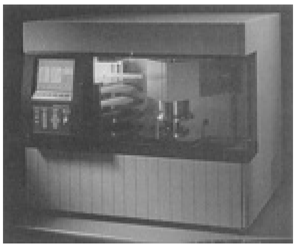


Fig. 10 A fully automatic polishing system

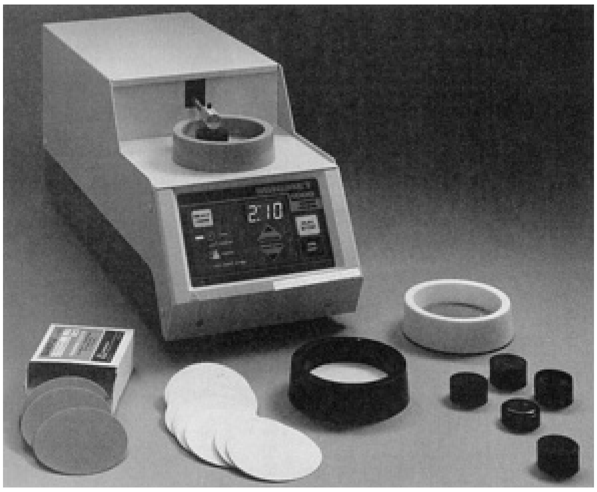


Fig. 11 An automatic single-specimen grinder/polisher

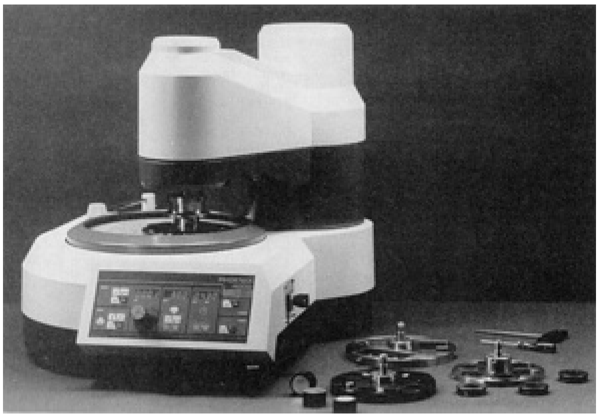


Fig. 12 A semi-automatic grinder/polisher

Polishing Cloths. The requirements of a good polishing cloth include the ability to hold an abrasive, long life, absence of any foreign material that may cause scratches, and absence of any processing chemical (such as dye or sizing) that may react with the specimen. More than a hundred cloths of different fabrics (woven or nonwoven) with a wide variety of naps (or napless) are available for metallographic polishing. Napless or low-nap cloths are recommended for rough polishing using diamond abrasive compounds. Low-, medium-, and occasionally high-nap cloths are used for final polishing, but this step should be as brief as possible to minimize relief.

Polishing Abrasives. Polishing usually involves the use of one or more of the following abrasives: diamond, aluminum oxide (Al_2O_3), magnesium oxide (MgO), and/or silicon dioxide (SiO_2). For certain materials, cerium oxide, chromium oxide, or iron oxide may be used. With the exception of diamond, these abrasives normally are used in a distilled-water suspension. If the metal to be polished is not compatible with water, other suspensions, such as ethylene glycol, alcohol, kerosene, or glycerol, may be required. The diamond abrasive should be extended only with the carrier recommended by the manufacturer.

Electrolytic Polishing

Even with the most careful mechanical polishing, some disturbed metal, however small the amount, will remain after preparation of a metallographic specimen. This remainder is no problem if the specimen is to be etched for structural investigation, because etching is usually sufficient to remove the slight layer of disturbed metal. If the specimen is to be examined in the as-polished condition using polarized light or if no surface disturbance can be tolerated, either electrolytic polishing (also called "electropolishing") or chemical polishing is preferred. Alternatively, vibratory polishing with (basic) colloidal silica, acidic alumina suspensions, or attack polishing agents added to these abrasives (or to α- or γ-alumina suspensions) will remove minor amounts of residual damage providing good polarized light response. A simple laboratory setup (Fig. 13) is sufficient for most electropolishing requirements, and the more sophisticated commercial units (Fig. 14) are all based on the same principle. Direct current from an external source is applied to the electrolytic cell under specific conditions, and anodic dissolution produces leveling and brightening of the specimen surface.

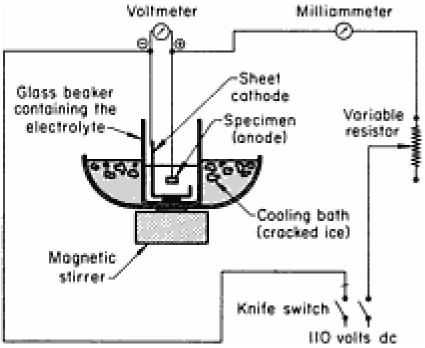


Fig. 13 Simple laboratory system for electropolishing and electroetching

Fig. 14 A commercially available electrolytic polishing and etching system

Not all materials respond equally well to electrolytic polishing. Wrought solid solution-type alloys, such as aluminum, nickel, nickel-iron, and titanium alloys, are particularly good candidates for electrolytic polishing. Electropolishing is usually reserved for single-phase alloys, because second phases and inclusions may be preferentially attacked during polishing.

Chemical Polishing

Chemical polishing involves simple immersion of a metal specimen into a suitable solution to obtain a metallographic polish. The results of chemical polishing are similar to those of electropolishing. They vary from an etched specimen surface that has been macrosmoothed but not brightened to a bright dipped surface that has been brightened but not macrosmoothed.

Etching

Metallographic etching encompasses all processes used to reveal particular structural characteristics of a metal that are not evident in the as-polished condition. Examination of a properly polished specimen before etching may reveal structural aspects, such as porosity, cracks, and nonmetallic inclusions. In certain nonferrous alloys, grain size can be revealed adequately in the as-polished condition using polarized light.

Electrolytic Etching. The procedure for electrolytic etching is basically the same as for electropolishing, except that voltage and current densities are considerably lower. The specimen is connected to be the anode, and some relatively insoluble but conductive material, such as stainless steel, graphite, or platinum, is used for the cathode. Direct-current electrolysis is used for most electrolytic etching, and for small specimens (13 by 13 mm, or $\frac{1}{2}$ by $\frac{1}{2}$ in., surface to be etched), one or two standard $1\frac{1}{2}$ V flashlight batteries provide an adequate power source. A setup like the one shown in Fig. 13 is usually all that is required.

Etching for Macrostructure. Macroscopic examination differs from microscopic examination in that it employs very low magnifications (up to approximately 50×) and is used for the investigation of defects and structure of a large area as opposed to a microscopic portion of that area. This technique is used to reveal solidification structure, flow lines, segregation, and structural changes due to welding, general distribution of sulfide inclusions, porosity, ingot defects, and fabricating defects. It is important that the investigator be aware that macroetching can exaggerate the size of inhomogeneities or defects that could lead to misinterpretation of the actual condition of the material.

Etching for Microstructure. In this article, microscopic examination is limited to a maximum magnification of 2500×--the approximate useful limit of light microscopy. Microscopic examination of a properly prepared specimen will clearly reveal structural characteristics, such as grain size, segregation, and the shape, size, and distribution of the phases and inclusions, that are present. The microstructure revealed also indicates prior mechanical and thermal treatment that the metal has received.

Etching is done by immersion or by swabbing (or electrolytically) with a suitable chemical solution that basically produces selective corrosion. Swabbing is preferred for those metals and alloys that form a tenacious oxide surface layer with atmospheric exposure, such as stainless steels, aluminum, nickel, niobium, and titanium and their alloys. It is best to use surgical grade cotton that will not scratch the polished surface. Etch time varies with etch strength and can only be determined by experience. In general, for high magnification examination, the etch should be shallower, while for low magnification examination a deeper etch yields better image contrast. Some etchants produce selective results in that only one phase will be attacked or colored. A vast number of etchants have been developed; the more commonly used etchants will be listed in this article (see also ASTM E 407).

Macroscopic Examination

There are aspects of structure, termed macrostructure, which can be observed with the unaided eye. Macrostructural examination is often a prelude to microstructural examination but also includes routine quality tests for material acceptance. These tests may also be useful for failure studies and research programs. The most common macrostructural tests include macroetching, sulfur printing, lead exudation, and fracture tests.

Macroetching is used to detect variations in soundness, chemistry, hardness, or strain. A disk is cut from the part, smooth ground, and subjected to etching with an appropriate solution. In a wrought product, a disk cut perpendicular to the deformation axis (i.e., transverse) is most commonly chosen as it reveals conditions that vary around the product. Less commonly, a section along the centerline parallel to the deformation axis will be chosen to better reveal segregation, which usually elongates with deformation and is more readily detected in this way. A finely polished surface is not required. On the other hand, a saw-cut surface, due to its roughness, will permit observation of only the coarsest features. A smoothly ground surface is best. For small products, a mounted and polished metallographic section will reveal most macrostructural features when standard microstructural etching solutions are used.

Macroetchants tend to be rather strong in concentration compared to microetchants, so that contrast is adequate for visual examination. Generally, the depth of etch attack of a macroetchant is substantially greater than for microetchants. Macroetchants may be used at room temperature or at temperatures up to about 80 °C (180 °F) depending upon the purpose of the study and the nature of the material. As an example, to study the macrostructure of weldments in ferrous alloys, macroetching with an aqueous 10% nitric acid solution at room temperature for 30 to 60 s is preferred. However, to evaluate the macrostructural soundness of a steel billet, hot acid etching with an aqueous 50% HCl solution at 70 to 80 °C (160 to 180 °F) for 15 to 30 min is preferred. Macroetching solutions for many metals can be found in ASTM E 340 and in other standard compilations.

Evaluation of the macrostructure of steel forgings, billets, bars, and continuously cast products is defined in various standards, such as ASTM E 381, MIL-STD-430A, ASTM A 561, and ASTM A 604. Features are classified based on their location (center, random, or subsurface) and nature (bursts, inclusions, flake, pipe ring patterns, freckles, white spots, cracks, etc.). Macroetching can also be applied to cast metals to reveal the grain structure, dendrites, blowholes, pin holes, sand holes, shrinkage cavities, etc. In forged components, particularly closed die forgings, the flow pattern is often evaluated by macroetching a disk cut across the component and etching to reveal the flow lines. Welding processes are often evaluated by macroetching sections taken through test welds. In failure analysis, macroetching often detects unusual or unexpected features that contribute to or cause failures.

Contact Print Methods

Although a number of special contact print methods have been developed, the most commonly employed is the sulfur print, used to reveal the distribution of sulfur in a steel product. A smoothly ground disk, carefully cleaned, is covered by a sheet of photographic paper that has been soaked for 1 to 5 min in an aqueous 2% sulfuric acid solution (1 to 5% solutions can be used). The excess solution is allowed to drip off the paper. Then, the emulsion side of the paper is placed against the ground surface of the steel specimen and left in contact for 2 to 10 min, depending on the sulfur content of the steel. The lower the sulfur content, the longer the time of contact. Any bubbles under the paper must be moved to the edge using a roller, squeegee, or sponge being careful not to move the paper. The print is then peeled off carefully, washed in running water, fixed, washed, and dried. Details of the sulfur print method are given in ASTM E 1180.

The distribution of sulfur is shown by the presence of darkly colored areas of silver sulfide on the print. The print is a mirror image of the sulfur distribution. Voids, holes, or cracks may be represented by dark spots or lines due to hydrogen sulfide gas becoming trapped in these openings under the paper. Other printing methods have been developed, but their use is infrequent.

Microscopic Examination

Metallurgical microscopes differ from biological microscopes primarily in the manner by which the specimen is illuminated. Unlike biological microscopes, metallurgical microscopes must use reflected light. Figure 15 is a simplified ray diagram of a metallurgical microscope, while Fig. 16 shows a typical inverted metallurgical microscope ("metallograph"). The prepared specimen is placed on the stage with the surface perpendicular to the optical axis of the microscope and is illuminated through the objective lens by light from the source. The light is focused by the condenser lens into a beam that is made approximately parallel to the optical axis of the microscope by the half-silvered mirror. The light is then reflected from the surface of the specimen through the objective, the half-silvered mirror, and the eyepiece to the observer's eye.

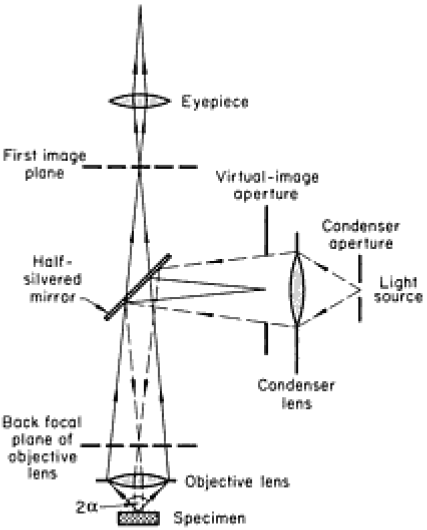


Fig. 15 Image formation in a metallurgical microscope employing brightfield illumination

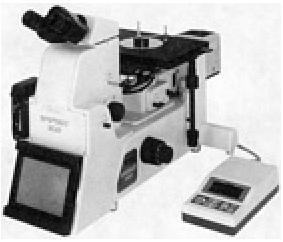


Fig. 16 Example of an inverted metallurgical reflecting microscope for photomicroscopy (referred to as a metallograph). Courtesy of C. Brandmaier, Nikon Inc.

Light Sources

The amount of light lost during passage from the source through a reflecting type of microscope is appreciable because of the intricate path the light follows. For this reason, it is generally preferable that the intensity of the source be high, especially for photomicroscopy. Several light sources are used, including tungsten-filament lamps, tungsten-halogen lamps, quartz-halogen lamps, and xenon arc bulbs.

Tungsten-filament lamps generally operate at low voltage and high current. They are widely used for visual examination because of their low cost and ease of operation.

Tungsten-halogen lamps are the most popular light source today due to their high light intensity. They produce good color micrographs when tungsten-corrected films are employed.

Xenon arc lamps produce extremely high intensity, and their uniform spectra and daylight color temperature makes them suitable for color photomicrography. The first xenon lamps produced ozone, but modern units have overcome this problem. Light output is constant and can only be reduced using neutral density filters.

Microscopic Techniques

Most microscopic studies of metals are made using brightfield illumination. In addition to this type of illumination, several special techniques (oblique illumination, darkfield illumination, opaque-stop microscopy, phase-contrast microscopy, and polarized-light microscopy) have particular applications for metallographic studies.

Köhler Illumination. Most microscopes using reflected or transmitted light use Köhler illumination, because it provides the most intense, even illumination possible with standard light sources. The reflected light microscope has two adjustable diaphragms, the aperture diaphragm and the field diaphragm, located between the lamp housing and the objective. Both diaphragms are adjusted to improve illumination and the image. To obtain Köhler illumination, the image of the field diaphragm must be brought into focus on the specimen plane. This situation normally occurs automatically when the microstructural image is brought into focus. The filament image must also be focused on the aperture diaphragm plane. This focus produces uniform illumination of the specimen imaged at the intermediate image plane and magnified by the eyepiece.

In brightfield illumination, the surface of the specimen is normal to the optical axis of the microscope, and white light is used. Figure 15 shows the ray diagram for this type of illumination in a standard type of bench microscope. Light that passes through the objective and strikes a region of the specimen surface perpendicular to the beam will be reflected back up the objective through the eyepieces to the eyes, where it will appear to be bright or white. Light that strikes grain boundaries, phase boundaries, and other features not perpendicular to the optical axis will be scattered at an angle and will not be collected by the objective. These regions will appear to be dark or black in the image. Brightfield is the most common mode of illumination used by metallographers.

Oblique illumination reveals the surface relief of a metallographic specimen. This process involves offsetting the condenser lens system or, as is more usually done, moving the condenser aperture to a position slightly off the optical axis. Although it should be possible to continually increase the contrast achieved by oblique illumination by moving the condenser farther and farther from the light axis, the numerical aperture of a lens is reduced when this happens because only a portion of the lens is used. For this reason, there is a practical limit to the amount of contrast that can be achieved.

Illumination also becomes uneven as the degree of obliqueness increases. Because differential interference contrast systems have been available, oblique illumination is rarely offered as an option on new microscopes.

Darkfield illumination (also known as dark ground illumination) often is used to distinguish features not in the plane of the polished-and-etched surface of a metallographic specimen. This type of illumination gives contrast completely reversed from that obtained with brightfield illumination: the features that are light in brightfield will be dark in darkfield, and those that are dark in brightfield will be light in darkfield. This highlighting of angled surfaces (namely, those of pits, crack, or etched grain boundaries) allows more positive identification of their nature than can be derived from a black image under brightfield illumination. Due to the high image contrast obtained and the brightness associated with features at an angle to the optical axis, it is often possible to see details not observed with brightfield illumination.

Polarized-Light Microscopy. is particularly useful in metallography, because many metals and metallic and nonmetallic phases are optically anisotropic. Polarized light is obtained by placing a polarizer in front of the condenser lens of the microscope and placing an analyzer before the eyepiece (Fig. 17). The polarizer produces plan-polarized light that strikes the surface and is reflected through the analyzer to the eyepieces. If an anisotropic metal is examined with the analyzer set 90° to the polarizer, the grain structure will be visible. However, viewing of an isotropic metal (cubic metals) under such conditions will produce a dark, extinguished condition. Polarized light is particularly useful in metallography for revealing grain structure and twinning in anisotropic metals and alloys and for identifying anisotropic phases and inclusions.

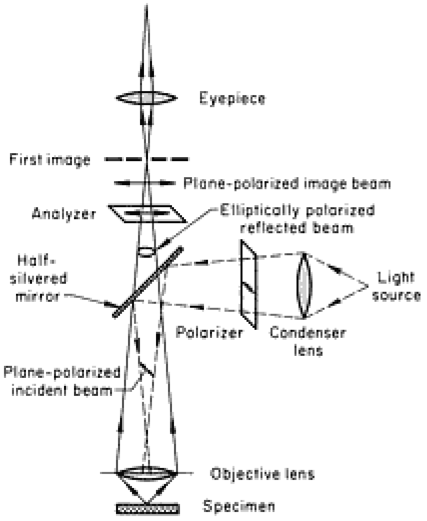


Fig. 17 Basic components of a polarizing light microscope

Differential Interference Contrast Microscopy. When crossed polarized light is used along with a double quartz prism (Wollaston prism) placed between the objective and the vertical illuminator, two light beams are produced that exhibit coherent interference in the image plane. This occurrence leads to two slightly displaced (laterally) images differing in phase (λ/2) that produces height contrast. The image produced reveals topographic detail somewhat similar to that produced by oblique illumination but without the loss of resolution. Images can be viewed with natural colors similar to those observed in brightfield, or artificial coloring can be introduced by adding a sensitive tint plate.

High-Temperature Microscopy. Several microscopes have been developed with devices that allow simultaneous heating and examination of specimens. These have permitted direct examination of thermal effects in metals, such as grain growth, precipitation reactions, phase changes, sintering, diffusion, and certain types of surface reactions. For some limited studies of this type, it is possible simply to surround the specimen with a small furnace and microscopically examine a polished surface. An alternative means of heating the specimen is by electrical resistance. Unfortunately, these simple methods have very limited usefulness because most metals and alloys oxidize at elevated temperatures, and oxidation must be avoided if unobstructed observations are to be made.

Heating in a vacuum presents a problem in that certain phases exposed on the surface of the specimen can evaporate and then condense on the viewing window thereby hindering observation. This situation can be partly overcome by using a double viewing window with the window nearer the specimen being removable and the remaining window being used for photography. Evaporation usually can be eliminated by operating in an inert-gas atmosphere; however, to prevent surface oxidation or contamination, the inert gas generally must be of very high purity.

A serious problem in high-temperature microscopy is potential damage to the microscope parts, particularly the objective lens, by the high temperatures. This danger is partly corrected by water cooling the parts of the hot stage near the objective; however, high magnifications are still not possible because the short working distances of most objectives do not permit examination through the viewing windows. To overcome this, long-working-distance objectives have been used. The most widely used type employs a reflecting concave mirror in conjunction with a standard objective.

Low-Temperature Microscopy. Certain reactions that occur in metals at low temperatures can be observed by microscopy. Stages have been constructed for this purpose; most are either adaptations of high-temperature stages or similar to them. Generally a refrigerant, such as liquid nitrogen, cools the stage that holds the specimen. A thermocouple on the specimen measures the temperature controlled by the supply of refrigerant. Low-temperature microscopy has found only limited use in metallography.

Straining Stages. Several other devices can be fitted to the stages of microscopes so that a specimen can be viewed while experiments are being performed on it. Stages constructed so as to allow straining of a specimen while it is being viewed have been particularly useful for studies of deformation, twinning, slip, and strain-induced transformations. Because of the development of scanning electron microscopes (SEM), these types of experiments are more commonly performed within the SEM.

Interferometry is the most sensitive and accurate optical method of measuring the microtopography of surfaces. Two interference methods are in common use in metallography: the two-beam and the multiple-beam methods.

Figure 18 shows the principles of the two-beam method. In a two-beam interferometer, monochromatic light from the source is split into two beams. One beam travels through the microscope objective to the specimen and then is reflected back through the objective and into the eyepiece. The other beam passes through an identically matched objective onto an optically flat reference plate and then back through the same objective and is directed by the beam splitter to the eyepiece. The two beams meet in the eyepiece and either reinforce each other (where the optical-path difference between them is equal to, or a multiple of, half the wavelength of the monochromatic light) or interfere with each other (where the optical-path difference does not satisfy the above conditions). From this reinforcement or interference, contour lines are formed with each line connecting points of the same level. The difference in height between fringes is one-half the wavelength of the light. Thallium light, which has a wavelength of 540 nm, is commonly used. It is usually possible to measure to an accuracy of one-tenth of a displacement, which means that differences in height of about 27 nm can be measured.

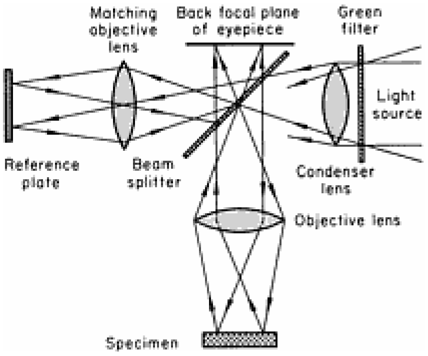


Fig. 18 Principle of two-beam interferometry

Figure 19 shows the principles of multiple-beam interferometry. Instead of creating interference between two light beams, the multiple-beam method produces interference among many beams. An optically flat reference plate that is partly transmitting and partly reflecting to light is placed onto the surface of the specimen. The plate and the specimen are positioned slightly out of parallel but usually by not more than one or two wavelengths. Several objectives with reference plates built into them are commercially available for use on standard metallurgical microscopes. Monochromatic light is directed perpendicular to the specimen surface through the objective. Some of this light is reflected from the surface of the reference plate and into the eyepiece of the microscope, whereas most of the light passes through the plate and onto the specimen. A series of reflections occurs between the reference plate and the specimen, such that with each reflection some of the light passes through the reference plate and into the eyepiece of the microscope. This light either reinforces or interferes with the light reflected from the surface of the plate, and contour lines result. If the components are correctly positioned, the multiple-beam method can produce such fine fringes that displacements as small as 1/100 of the fringe displacement can be measured, thereby allowing measurements of differences in level as small as about 3 nm.

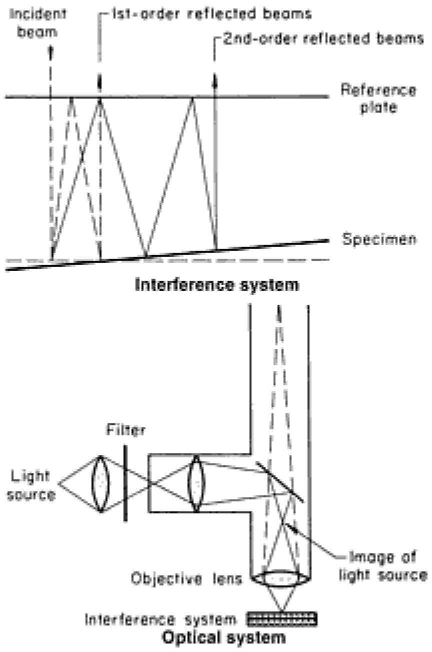

Incident beam
1st-order reflected beams
2nd-order reflected beams
Reference plate
Specimen
Interference system
Filter
Light source
Image of light source
Objective lens
Interference system
Optical system

Fig. 19 Principle of multiple-beam interferometry

Macrophotography

Metallographers frequently need to take low magnification photographs of components, etch disks, fractures, and so forth, using either black and white or color film. A wide variety of approaches are possible. If the pictures are made on site, for example at an accident investigation, ordinary 35 mm medium-format or large-format cameras may be used, aided by various light sources, if needed. A macrotype lens for close-up work is very useful.

In the laboratory, it is helpful to use a camera stand, such as the Kaiser stand (Fig. 20). Generally, the most critical aspect of this work is adjustment of the lighting so that it is uniform, the desired details are visible, and undesirable shadows are minimized. A light box is a useful aid for such work.

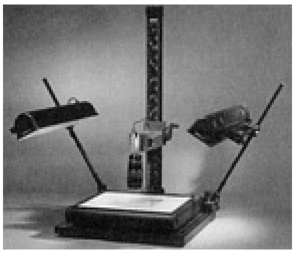


Fig. 20 Versatile camera stand for macrophotography

Many stereoscopic microscopes can be equipped with a camera for taking pictures at magnifications under 50×. Some microscopes have a trinocular head where the camera is inserted into the third port (the other two are for the eyepieces).

In all work, it is important to use a light meter to gauge the proper exposure. This precaution greatly reduces film waste and improves results. Generally, depth of field is an important criterion in macrophotography, because many objects to be photographed are not flat. Basically, depth of field improves as the *f*-number of the lens is increased and is reduced as the magnification increases. The focal length of the lens has a minor influence on the depth of field. However, as long focal length lenses produce a greater working distance between subject and lens, they are preferred. The depth of detail (the ability to separate detail throughout the depth of focus), is usually optimal between about *f*/10 and *f*/16, although this range varies with magnification.

A wide range of films can be used as well as electronic media. Historically, wet-processed films have yielded the finest results, and that is still true today. If enlargements are required, particularly for sizes greater than 8 by 11 in. (21.5 by 28 cm), a medium-format film or a large-format film is better. Generally, panchromatic films are best for black-and-white work. For color work, the film type must be compatible with the color temperature of the lighting. Digital cameras are becoming popular, and rather high pixel densities are available at a reasonable price. Alternatively, a charge-coupled device (CCD) camera can be mounted on a macro lens to provide images to a capture system. Digital formats are very convenient especially for annotation of images and ease of image storage, but very high quality printers, approaching the resolution of photographs, are still rather expensive.

Microphotography

All metallographs come equipped with one or more camera ports, as well as provisions for attaching CCD cameras (or other types, although the CCD is by far the most common type used). While biologists frequently use 35 mm cameras to record microstructures, they are less popular with metallographers. A small percentage of metallographers still prefer to use wet processed sheet film, usually 4 by 5 in. (10 by 12.5 cm) size. Orthochromatic film is no longer available in this size, and panchromatic films must be employed. These are less convenient to use because loading, unloading, and developing must be done in total darkness. Otherwise, results are the same. Contact printing is most commonly performed.

The majority of metallographers switched to instant films (Polaroid), which were introduced in the 1960s. At that time, few (if any) metallographs had exposure meters, and wastage was significant because instant films have no latitude (exposures must be exactly controlled to get good images, unlike wet processed films). Instant films are convenient because dark room work is avoided. However, except for the P/N type, there is no negative so extra prints cannot be made in the same way as by traditional photography. Instead, multiple photographs must be made anticipating future needs.

Electronic photography is becoming very popular and will eventually become the dominant mode as it features all the convenience of instant photography with none of the disadvantages. The biggest problem now is the cost of a high quality, high resolution printer, but that should become less of a problem in the future.

Principles of Technique Selection in Mechanical Polishing

THREE DISTINCT OPERATIONS are involved in determining the microstructure of metals with the use of a light optical microscope: preparation of a section surface; development of the structure on that surface, usually by chemical etching; and microscopic examination. The effectiveness of the examination is dependent upon these prior steps. Improper specimen preparation will impair examination and may result in artifact structures being confused as true structure. Etching must also be performed properly, although poor etch results are usually obvious and can be easily corrected. Selection of the best etchant for a given specimen is more difficult, generally requiring trial and error based on past experience.

The primary objective of a preparation procedure must be to produce a surface that fully represents the microstructure as it existed in the metal before sectioning. All structural features characteristic of the metal must be detectable, and false structures must not be introduced. This requirement is more demanding than the mere production of what appears to be a highly polished surface.

The main purpose of this section is to illustrate how objective experiments and comparisons can be used to develop preparation procedures that not only give better results but also are simpler and less laborious to use. The emphasis is on principles that can be used as guides in the development of practical preparation procedures, rather than on the details of those procedures.

Abrasion Damage and Abrasion Artifacts

Figure 21(a) shows the general pattern of a surface layer that has been plastically deformed for abraded cartridge brass (Cu-30%Zn), an alloy in which the effects of prior plastic deformation, generally from sectioning or grinding, can readily be revealed by a range of etchants. This micrograph highlights several characteristic features. The shallow, dark-etching, unresolved band contouring the surface scratches is known as the outer fragmented layer; it is a layer in which the strains have been very large. Beneath this layer extends a layer in which the strains have been comparatively modest, and in which the strains tend to concentrate in rays extending beneath individual surface scratches. The bands of etch markings, known to develop at the sites of slip bands, show the strains as well as the more diffuse rays, known to indicate the presence of kink bands. These effects extend to many times the depth of the surface scratches.

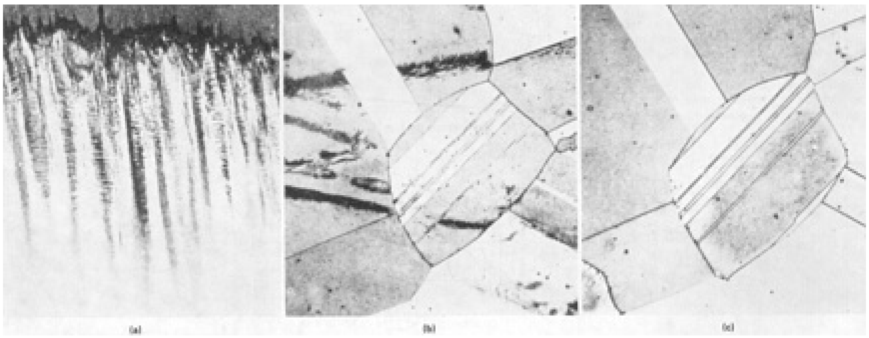


Fig. 21 Annealed cartridge brass (Cu-30%Zn). (a) Taper section (horizontal magnification, 600×; vertical magnification, 4920×) of surface damage from abrasion with 220-grit silicon carbide paper. (b) Micrograph taken after abrasion on 220-grit silicon carbide paper and then polished until about 5 μm of metal was removed. The banded markings are abrasion artifacts (false structures). (c) Micrograph showing the true microstructure taken after abrasion on 220-grit silicon carbide paper and then polished until about 15 μm of metal was removed. All three specimens were etched in an aqueous ferric chloride solution.

Figures 21(b) and 21(c) show the importance of the surface damage shown in Fig. 21(a). A specimen of annealed cartridge brass was abraded on 220-grit silicon carbide paper and then polished to remove a surface layer about 5 μm (200 μin.) thick. All traces of the abrasion scratches were removed; and, ostensibly, a satisfactory surface was produced, but the bands of deformation etch markings (Fig. 21b) appeared when the surface was etched. When layers of greater thickness were removed during polishing, these bands gradually reduced in number and intensity, and eventually were eliminated, as shown in Fig. 21(c), which shows the true structure.

The deep abrasion-damage effects discussed thus far cause difficulties in only a limited range of alloys, but effects due to an outer fragmented layer are likely to be found in all metals. Certain distinctive artifacts caused by disturbance in the outer fragmented layer are observed in pearlitic steels. Taper sections of abraded surfaces of these steels have shown that the cementite plates of pearlite may simply be bent adjacent to some scratches and may be completely fragmented adjacent to others.

Austenitic steels generally are quite susceptible to abrasion artifacts, and the common etchants reveal effects due to prior deformation with considerable sensitivity. The structure of a typical abrasion-damaged layer is comparable to that for brass. A shallow, unresolved layer contours the surface scratches, and deep rays of deformation etch markings extend beneath the surface scratches. Bands of these deformation etch markings may appear in a final-polished surface as abrasion artifacts. Good abrasion practice and efficient polishing processes are required for removal of the abrasion artifacts in acceptable polishing time.

Embedding of Abrasives. The points of the contacting abrasive particles of an abrasive paper fracture readily during abrasion, and these fragments may become embedded in the surface of a very soft metal, such as lead (Fig. 22) or annealed high-purity aluminum. Embedded particles are difficult to discern in the surface by light microscopy, but a surface with a high concentration of embedded abrasive characteristically has a rough, torn appearance.

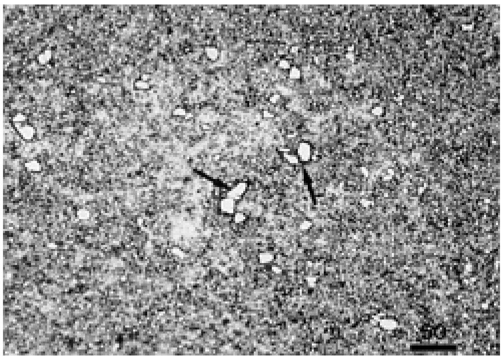


Fig. 22 Embedding of SiC (arrows) abrasive in a nearly pure lead specimen (prepared up to 1 μm diamond finish). 200×

Preparation Damage

The mechanical preparation procedures commonly used in metallographic practice remove metal by mechanical cutting processes analogous to those occurring during abrasion. Grinding and polishing always produce a series of scratch grooves on the surface of the specimen; these scratches may be difficult to detect by light microscopy, particularly with bright-field illumination. Moreover, a plastically deformed, damaged layer is also introduced; the layer produced by mechanical polishing is much shallower than that produced by grinding, but its structure is similar. A layer analogous to the outer fragmented layer in ground surfaces can be recognized contouring the surface scratches, and there are occasional rays of deformed metal extending to greater depths, many times the depth of the polishing scratches. The presence of this damaged layer has important practical consequences--it affects the response of the surface to etching.

Even on well-prepared surfaces, a very fine layer of damaged material will remain that can be removed by mechanical-chemical polishing ("attack" polishing). In mechanical-chemical polishing, a small amount of dilute etchant is used together with the abrasive suspension. The etchant attacks the surface chemically while the abrasive removes the product of this chemical attack.

An excessive amount of the chemical component in a mechanical-chemical process may cause detrimental effects, such as severe etch pitting. Proper balance between the mechanical and chemical components can preserve most of the benefits provided by mechanical polishing and yet produce a damage-free surface--a most desirable combination in a final-polishing stage.

An alternative to attack polishing is provided by modern non-neutral polishing suspensions, for example, colloidal silica with a pH of 9.5 to 10 and acidic alumina suspensions with a pH of 2.5 to 3. A dilute etchant can also be added to these abrasive suspensions to further enhance metal removal. These suspensions are particularly affective when used with a vibratory polisher.

Enlargement of Polishing Scratches by Etching. It is a frequent annoyance in metallographic practice to find that a surface, which appeared to be free of scratches when examined as-polished with brightfield illumination, turns out to be severely scratched after etching. The scratches were actually there all the time, but they were too fine to be detected when the specimen was in the unetched condition; they were enlarged, or shown in greater contrast, by etching.

In some cases, the etchant is revealing the damage present beneath scratches removed during preparation. Scratches are attacked preferentially during etching because of the disturbed metal, or damaged layer, associated with them. Severity of attack varies directly with the ability of the etchant to reveal deformation. Color "tint" etchants are perhaps the most sensitive etchants to preparation-induced damage not fully removed during preparation. The appearance of scratches also depends on the etching time. A certain minimum etching time is necessary to develop the scratches fully; thereafter, the scratches recede with increasing etching time, because etching progressively removes the damaged layer. It may be difficult to distinguish scratches enlarged by the final polishing stages from scratch traces introduced during the previous polishing stage. The problem can be resolved by making the earlier set of scratches unidirectional and parallel to a known direction in the specimen surface. The scratch traces can then be recognized. This technique only works with manual preparation because automatic devices produce randomly oriented scratch patterns.

Flatness. Quality in polishing practice means a surface that is adequately free from confusing polishing scratches and sufficiently flat for all constituents and local regions to be examined properly. Different types of flatness problems are encountered in metallography. Nonflat situations may arise in a variety of ways, but they are generally associated with microstructures that exhibit local hardness variations or at free surfaces. Height differences can be markedly influenced by the preparation practice. This condition is usually called "relief." For example, hard particles (oxides, carbides, nitrides, or intermetallics) in a softer matrix stand above ("proud") the matrix in positive relief, while soft particles (sulfide inclusions, soft metal insoluble phases, graphite, etc.) in a harder matrix lie below the matrix in negative relief. Negative relief is common at surfaces, such as exterior specimen surfaces, but also at interior surfaces, such as cracks or pores. Even if there is no hardness difference at these edges, they can easily become "rounded" (negative relief) due to a lack of support during preparation.

These conditions can be controlled to a large extent by the preparation procedure used. Flatness is improved if napless, or very low-nap, surfaces are employed, particularly in the polishing stage. Figure 23(a) shows the structure of a braze between Monel and type 304 stainless steel prepared using a procedure to minimize relief, while Fig. 23(b) shows the same specimen using a procedure that will create height differences where there are hardness differences.

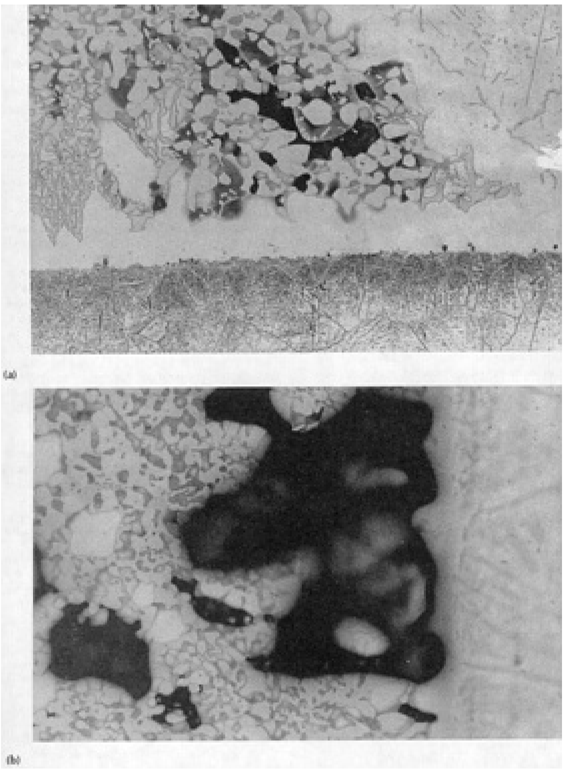


Fig. 23 Example of control of relief (a) and creation of excessive relief (b) in a braze between 304 stainless steel and Monel. Glyceregia etch, 200×

Retention of Graphite in Gray Iron. Graphite in cast iron can be damaged severely during the abrasion stage of preparation; however, it is possible by suitable choice of abrasion process to obtain a reasonably true representation of the structure. There remains the problem of retaining the graphite during polishing. The solution to the problem depends heavily on the length of the nap of the polishing cloth.

Graphite flakes in a gray iron invariably look much larger when long-nap cloths (Fig. 24a) are used for polishing. This apparent enlargement is caused by erosion, which occurs at the interface between graphite and matrix, producing an enlarged cavity from which the flake itself eventually is removed. With a cloth of reasonably short nap, many of the flakes are well retained, although some may appear to be slightly enlarged. Examination of sections of such a surface indicates that flakes aligned perpendicular to the surface are well sectioned but that slight erosion occurs around flakes that happen to be acutely aligned to the section surface. Correct representation of the graphite flakes is obtained after polishing with a napless cloth (Fig. 24b). Only a limited number of abrasives, notably diamond abrasives, produce satisfactory results on napless cloths. The use of napless cloths for all of the polishing steps yields the best retention of graphite.

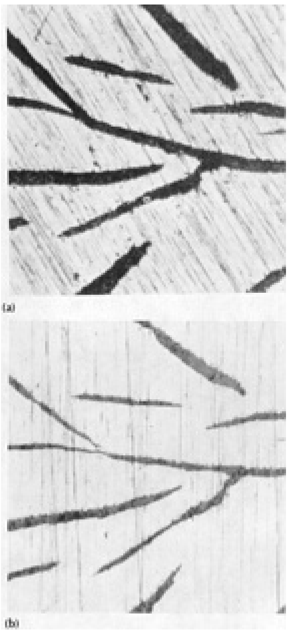


Fig. 24 Retention of graphite in cast iron. (a) Coarse graphite flakes in a gray iron specimen that was polished with a long-nap cloth. Note enlarged cavities where the graphite phase has been torn out. (b) Well-preserved graphite flakes in a gray iron specimen that was polished with a napless cloth. Both specimens not polished, not etched, and shown at 100×

Removal of Scratches. Only rarely is it required that final-polished surfaces be completely free of scratches, particularly in production work. A more reasonable and practical requirement is that no coarse scratches should be detectable under the particular conditions of examination. Attainment of this objective will depend on the specimen material (more difficult with soft materials), the etching conditions (more difficult with etchants that are sensitive to deformed structures), and the optical conditions (more difficult with optical conditions that are sensitive to surface irregularities, such as darkfield and polarized light). A metallographer should have available a variety of final-polishing processes capable of producing increasingly higher qualities of finish from which to select the most suitable for a particular need.

Vibratory polishing methods are attractive for final polishing because they operate automatically. An advantage of vibratory polishing is that it can be adapted to chemical-mechanical polishing. The important variables in vibratory polishing are the abrasive, the nature of the liquid in which the abrasive is suspended, and the load applied to the specimen.

Not all polishing cloths can be used on a vibratory polisher. Low- to medium-napped cloths are generally used. Colloidal silica works very well on a vibratory polisher, partly because it stays in solution, being a colloid and partly because of its basic pH, around 9.5 to 10, which adds a chemical action to mechanical polishing.

Electrochemical Differences. A further example of chemical effects arising during mechanical polishing is found in specimens containing constituents that differ considerably in their electrochemical characteristics. In galvanized steels, marked electrochemical effects arise between the zinc of the coating and the steel base metal. Severe etching of the coating occurs when the specimen is polished with an aqueous suspension or cleaned with water. This effect can be eliminated by using a suspending liquid that has a pH very close to 7.0, thus suppressing electrochemical effects. This pH can be achieved with the use of a standard buffer solution. Others prefer to avoid the use of water in at least the final preparation step.

Edge Retention. With few exceptions, the abrasion rates of the plastics in which metallographic specimens are mounted are much greater than those of metals. The plastic abrades to a lower level than the metal, and rounding of the specimen edge occurs to adjust for differences in level. The degree of edge rounding may be increased or decreased during polishing; long-nap polishing cloths increase edge rounding.

However, the abrasion rates of different types of plastics differ significantly, and edge retention can be improved by choosing a mounting plastic that has an abrasion rate matching as closely as possible that of the specimen. For example, improved edge retention is obtained with the change from a phenolic to a thermosetting epoxy. Metals that have very low abrasion rates, such as chromium and tungsten, show poorer edge retention than steels. Metals that have higher abrasion rates, such as copper and aluminum, show good edge retention even when mounted in phenolic plastics.

Attempts have been made to reduce the difference in abrasion rate between the specimen and mount to improve edge retention. Mounting specimens using a press that cools the specimen back to near room temperature under pressure virtually eliminates the shrinkage gaps between specimen and mount, which has produced a vast improvement in edge retention.

Layers and Coatings. Determination of the structure of a surface, coating, or a layer of oxide (scale) on a specimen is sometimes the principal reason for metallographic examination. A specimen with such layers presents a problem in edge retention. An oxide layer is usually friable, and thus susceptible to chipping and cracking during preparation. In these cases, impregnation with epoxy resin is recommended. Because the detection of porosity or cracking in the layer is an important feature of the examination, it is essential to avoid the development of preparation artifacts that might be mistaken for such features. The development of such artifacts during abrasion is possible, because grinding with standard abrasive papers may result in extensive chipping of the oxide layer. Polishing with diamond abrasives on a hard napless cloth ensures that a high degree of surface flatness will be maintained and that no polishing damage will be introduced.

Electrolytic Polishing

ELECTROLYTIC POLISHING, also called electropolishing, is useful with stainless steels, copper alloys, aluminum alloys, magnesium, zirconium, and other metals that are difficult to polish by conventional mechanical methods. The electrolytic technique can completely remove all traces of worked metal remaining from the cutting, grinding, and mechanical polishing operations used in preparing specimens. When electropolishing is used in metallography, it is usually preceded by at least preliminary mechanical polishing and is often followed by etching.

Mechanism

Although the mechanism of electropolishing is not understood in all its aspects, the process is generally considered to include both a leveling (or smoothing) action and a brightening action. According to a theory developed by P.A. Jacquet in 1936, smoothing is accomplished by preferential solution of the "hills" or ridges on a rough surface, such as those that result from grinding. When a rough surface is made the anode of a suitable electrolytic cell, a viscous liquid layer immediately adjacent to this surface is produced by the reaction between metal and electrolyte. This layer of solution, known as the polishing film, has a greater electrical resistance than the remainder of the solution and controls the smoothing action. The brightening action is related to the elimination of irregularities as small as about 0.01 μm and to the suppression of etching on the metal surface. This behavior is generally attributed to the formation of a thin, partly passivating film directly on the surface of the metal and following its contours.

Current-Voltage Relations. In electropolishing, current-voltage relationships vary in different electrolytes and for different metals. Figure 25 shows the simple relation wherein polishing occurs over an extensive continuous range of currents and voltages. At low voltages, a film forms on the surface and little or no current passes; thus, etching occurs but not polishing. At higher voltages, polishing occurs. The perchloric acid electrolytes used for aluminum conform to this relation.

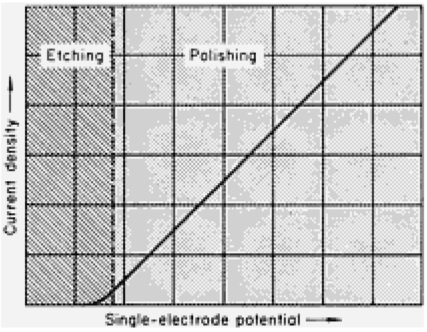


Fig. 25 Schematic relationship between current density and the single electrode potential for electrolytes having polishing action over a wide range of voltages and currents

A more complex relation, frequently encountered, is shown by the curve in Fig. 26. This curve depicts cell voltage as a function of anode current density for electropolishing of copper in an aqueous solution of orthophosphoric acid using a potentiometric circuit. Five distinct regions can be distinguished on the cell voltage-current density curve. In the region A-B, current density increases with the potential, some metal dissolves, and the surface has a dull etched appearance. The region B-C reflects an unstable condition, while region C-D indicates a stable plateau at which the polishing film, previously formed, reaches a point of equilibrium and polishing occurs; during the latter stage, current density remains constant. Optimum polishing conditions occur along C-D near D. In the region D-E, gas bubbles evolve slowly, breaking the polishing film and causing severe pitting. Polishing with rapid evolution of gas is represented by the region E-F.

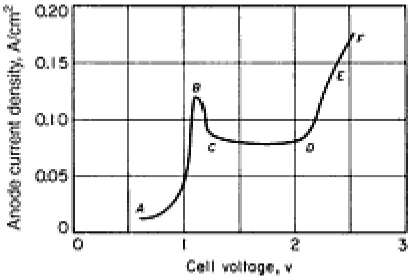


Fig. 26 Cell voltage as a function of anode current density for electropolishing of copper in orthophosphoric acid (900 g/L of water) using a potentiometric circuit

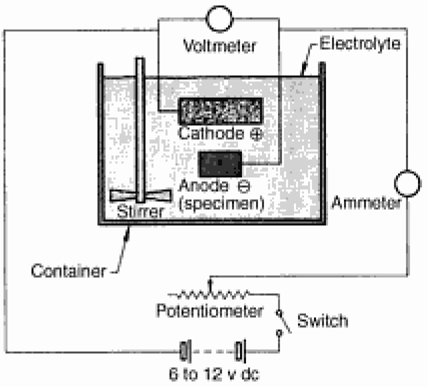
Electrolytes of the sulfuric-phosphoric acid and chromic-acetic acid types used for stainless steels also typify the complex, multistage relationship shown in Fig. 26. In establishing voltage-current relationships like those in Fig. 25 and 26, electrolysis must be allowed to proceed under fixed conditions until enough metal has dissolved to produce a steady state condition at the anode.

Apparatus and Procedure

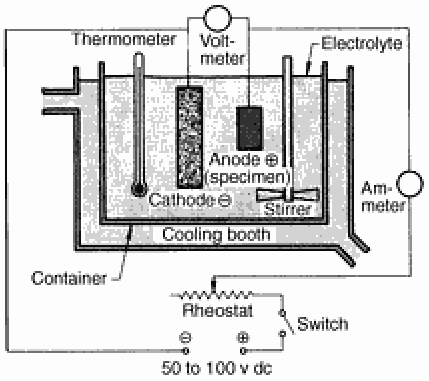
The electrical equipment used for electropolishing can vary from the simplest arrangement of dry cells to elaborate arrays of rectifiers and electronic control devices. Various types of apparatus are available commercially. The choice of equipment depends on the number and type of specimens to be treated and the versatility and control desired.

Current Source. Direct current is usually employed. The current source may consist of a battery, a direct-current generator, or a rectifier. In general, a battery supply is used for low voltages only, because a bank of batteries would be needed to produce higher voltages. These three types of current source deliver a constant supply of direct current.

Electrical Circuits. Two typical circuits, one for low and one for high current densities, are shown in Fig. 27. For solutions in which a small drop in potential occurs across the cell, a potentiometric circuit, for low current densities, is more suitable (Fig. 27a). Conversely, when the drop in potential across the cell is high, a series circuit, for high current densities, should be used (Fig. 27b). Provision must be made for controlling both voltage and current.



(a) Potentiometric circuit (for low current densities)



(b) Series circuit (for high current densities)

Fig. 27 Two electrical circuits and equipment arrangements for electropolishing metallographic specimens

Alternating current is used for electropolishing and electroetching the metals of the platinum group (platinum, iridium, palladium, rhodium, osmium, and ruthenium), using a series circuit and schematic arrangement as shown in Fig. 27(b) with an alternating current source.

The electrolytic cell is simply a container for the electrolyte, in which are suspended the cathode and the anode. The cell is usually made of glass, but it may be polyethylene or polypropylene for solutions containing fluoride ions. Sometimes a stainless steel cell is used, which may serve also as the cathode. Frequently, the cell is surrounded by water or an ice bath or is cooled in some other manner.

The specimen to be polished (anode) should be arranged for quick removal from the electrolyte. The electrical connection to the specimen should be simple and easily broken so that the specimen can be rinsed immediately after polishing. The cathode should be made of a metal that is inert in the electrolyte being used; stainless steel is satisfactory for most applications.

For many applications, stirring, pumping, or air agitation of the electrolyte is necessary. During electropolishing under steady-state conditions, the anodic reaction products accumulate on the surface of the polished metal. Often, natural diffusion and convection processes cannot remove these products from the anode surface into the bulk of the electrolyte rapidly enough, and excessive accumulation of reaction products interferes with the electropolishing process. The use of agitation usually requires an increase in the current density in order to maintain a sufficiently thick polishing film.

Arrangement of Anode and Cathode. Two ways to position the specimen (anode) and the cathode are shown in Fig. 27. In each arrangement, only the portion of the specimen to be polished is exposed to the electrolyte. In Fig. 27(a), the surface to be polished is horizontal and facing upward, toward the cathode. This arrangement helps to maintain a stable layer near the surface being polished, and is ordinarily used when polishing occurs under a viscous layer. In Fig.

27(b), the surface to be polished is vertical and facing toward the cathode. This arrangement is sometimes used when polishing occurs with gas evolution, because it allows easy escape of the gas bubbles.

Mounting of Specimens

Only the portion of the specimen to be polished should be in contact with the electrolyte. Small specimens may be mounted by conventional molded-plastic-mounting procedures, for ease in handling for mechanical preparation and subsequent electropolishing. Electrical contact can be made through a small hole drilled through the back of the mount into the metal specimen, or by the use of an indirect connection (Fig. 28).

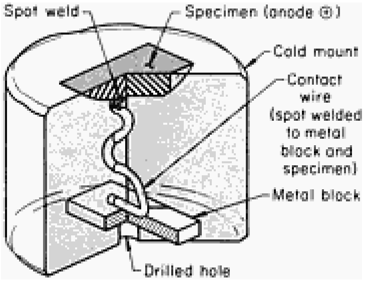


Fig. 28 Example of a method for creating electrical conductivity of a small specimen in a polymeric mount

When specimens are mounted in plastic, the possibility of violent reaction between the plastic and some electrolytes must be considered. For example, phenol-formaldehyde mounting materials, acrylic-resin mounting materials, and cellulose-base insulating lacquers and materials should not be used in solutions containing perchloric acid, because of the danger of explosion. Polyethylene, polystyrene, epoxy resins, and polyvinyl chloride can be used as mounting materials in perchloric acid solutions without danger.

Mounting of specimens in dissimilar metals is undesirable, because the metal in contact with the electrolyte is likely to interfere with polishing and also because fusible mounting alloys containing bismuth may be dangerously reactive in certain electrolytes that contain oxidizing agents. Bismuth-containing alloys may form explosive compounds in perchloric acid solutions.

In preparing an unmounted specimen for electropolishing, a suitable chemically inert, electrically insulating coating can be applied to all surfaces of the specimen (and specimen holder) except the surface to be polished. Plastic electrician's tape is also an effective stop off, being impervious to most electrolytes and readily removable from the specimen after electropolishing.

Development of Procedures for Electropolishing

Metallographers may be asked to electropolish a metal or alloy that has not previously been encountered. In developing a suitable procedure, the problem should be viewed in comparison with known procedures and with information gained through previous experience.

Effect of Alloy Type. It is generally helpful to compare the position of the major component of the alloy with elements of the same general group in the periodic table, and to study the phase diagram, if available, to predict the number of phases and their characteristics. Single-phase alloys are generally easiest to electropolish, whereas multiphase alloys are likely to be difficult or impossible to electropolish. Even minor alloying additions to a metal may profoundly affect the response of the metal to polishing in a given electrolyte.

General Principles. The possibility of polishing a metal and the conditions for polishing a metal in a given electrolyte can sometimes be ascertained by plotting current density versus electrode potential. The curve in Fig. 25 is typical of those electrolytes that polish over a very wide range or that will not polish at all. The curve in Fig. 26 is characteristic of those electrolytes that form an ionic film; polishing will occur between points C and D on this curve; polishing is usually best near point D.

After the polishing range is determined, the other constants, such as preparation, agitation, and time, can be determined experimentally. The amount of preparation required depends on the nature of the specimen and on the results desired.

Specimen preparation can be accomplished in many cases by grinding through a series of graded abrasives up to a 600 grit SiC paper finish. In other cases it is necessary or desirable to prepolish the specimen with 6 μm diamond before starting to electropolish. For some metals, it is best to completely polish the specimen mechanically and then use a brief electropolish stage to remove any remaining preparation-induced damage.

The surface to be polished should be clean to allow uniform attack by the electrolyte. To avoid contamination with oil from fingers, the specimen should be handled with forceps or tongs after final preparation for electropolishing.

Advantages and Disadvantages of Electropolishing

When properly applied, electropolishing can be a useful tool for the metallographer. The principal advantages of electropolishing include:

- For some metals, electropolishing can produce a high-quality surface finish that is equivalent to the best that can be obtained by mechanical methods.
- Once a procedure has been established, good results can be obtained with less operator skill than that required for mechanical polishing.
- There can be a marked saving of time if many specimens of the same material are to be polished sequentially.
- Electropolishing is especially suited for the softer metals, which may be difficult to polish by mechanical methods.
- No scratches are produced in electrolytic polishing. The absence of scratches is a definite advantage in viewing high-quality electropolished surfaces of optically-active materials with polarized light.
- Artifacts resulting from mechanical deformation--such as disturbed metal or mechanical twins, which are produced on the surface even by careful grinding and mechanical polishing--do not occur in electropolishing.
- Surfaces resulting from electropolishing are completely unworked by the polishing procedure. This feature is important in low-load hardness testing or x-ray studies.
- With some electrolytes, etching can be accomplished by simply reducing the voltage to approximately one-tenth the potential required for polishing, then continuing electrolysis for a few seconds.
- Electropolishing is frequently useful in electron metallography (where high resolution is often important) because it can produce thin undistorted metal surfaces.

Metallographic preparation by electropolishing is subject to several limitations; these should be recognized to prevent misapplication of the method and disappointment in the results. The principal disadvantages include:

- The chemicals and combinations of chemicals used in electropolishing are poisonous; many are highly flammable or potentially explosive. Only well-trained personnel thoroughly familiar with chemical laboratory procedures should be permitted to handle or mix the chemicals or to operate the polishing baths.
- The conditions and electrolytes required to obtain a satisfactorily polished surface differ for different alloys; hence, considerable time may be required to develop a procedure for a new alloy, if it can be developed at all. This limitation does not apply if appropriate procedures exist.
- In multiphase alloys, the rates of polishing of different phases often are not the same. Polishing results depend heavily on whether the second or third phases are strongly cathodic or anodic with respect to the matrix. The matrix is dissolved preferentially if the other phases are relatively cathodic, thus causing the latter to stand in relief. Preferential attack may also occur at the interface between two phases. These effects are most pronounced when phases other than the matrix are virtually unattacked by the polishing bath. The effects are reversed when the matrix phase is relatively cathodic.
- A large number of electrolytes may be needed to polish the variety of metals encountered by a given

laboratory.

- Plastic or metal mounting materials may react with the electrolyte.
- Electropolished surfaces are not flat but exhibit an undulating surface, and in some cases may not be suited for examination at all magnifications. Under some conditions, furrowing and pitting may be produced.
- Edge attack effects limit applications involving small specimens, surface phenomena, coatings, interfaces, and cracks.
- Attack around nonmetallic particles and adjacent metal, voids, and various inhomogeneities may not be the same as that of the matrix, thus exaggerating the size of the voids and inclusions.
- Electropolished surfaces of certain materials may be passive and difficult to etch.

Electrolytes

Formulations of electrolytes, sorted into eight groups, may be found in *Metallography, Structures, and Phase Diagrams,* Volume 8, *Metals Handbook,* 8th ed., p 30-31; *Metallography and Microstructures,* Volume 9, *ASM Handbook,* p 52-53; and ASTM E 1558. Other compilations of electrolyte compositions may be found in *Metallography: Principles and Practice,* by G.F. Vander Voort, McGraw-Hill, 1984. Preferred (or sometimes required) characteristics of an electrolyte are:

- It should be somewhat viscous.
- It must be a good solvent for the anode metal (the specimen) during electrolysis conditions.
- It should preferably not attack the anode metal when no current is flowing.
- It should contain one or more ions of large radii, such as $(PO_4)^{-3}$, $(ClO_4)^{-1}$, or $(SO_4)^{-3}$, and sometimes large organic molecules.
- It should be simple to mix, stable, and safe to handle (many effective electrolytes are deficient in these respects).
- It should function effectively at room temperature and not be sensitive to temperature changes.

Procedures and Precautions for Preparation and Handling of Etchants

IN THIS SECTION, the term *etchant* is used in its broadest sense, to include reagents used in metallographic work for microetching, macroetching, electropolishing, chemical polishing, and similar operations.

The formulations of etchants given elsewhere in this Volume are adequate for the majority of applications, but they may occasionally require modification. Adjustments in etchant composition (as well as in etching time and technique), based on the experience and skill of the metallographer, and magnification to be used, may be needed in order to obtain satisfactory results.

Expression of Composition

Etchants are generally either aqueous or alcoholic solutions containing one or more active chemicals (acids, bases, or salts). Liquids other than water or alcohol are used as solvents in some formulations. Compositions of most etchants described in this section are expressed in terms of the amounts of the substances to be used in preparing small quantities of these reagents. For etchants that are solutions of solid substances in liquids, the amounts of the solid substances are usually expressed in grams (g), and the amounts of liquids (or the total volumes of solution) are expressed in milliliters (mL). The liquids may be individual commercially available substances, or they may be stock solutions containing two or more substances. Compositions of some etchants that are prepared by mixing together two or more liquids are given in parts by volume or percentage by volume. Compositions of some etchants consisting of solutions of solid substances in liquids are described in terms of percentage by weight.

In long-established (although nonstandard) usage in metallography, such terms as 1%, 2%, and 4% have been used to describe the approximate strength of an etchant, such as picral, and are understood to mean 1, 2, and 4 g, respectively, of picric acid per 100 mL of alcohol.

Purity of Chemicals

In the preparation of solutions for microetching and electropolishing, recommended practice is to use chemicals meeting the requirements of NF (National Formulary), USP (U.S. Pharmacopoeia), laboratory or purified grades, or grades of still higher purity (reagent, ACS, or certified grades). The commercial or technical grades of certain special-purpose industrial chemicals (such as CrO_3 and synthetic methanol) are extremely pure and are equivalent to reagent, ACS, or certified grades for use in microetching and electropolishing. Where water is specified, distilled water is preferred because of wide variations in the purity of tap water. For macroetching, technical grades of chemicals are satisfactory, unless specifications indicate otherwise, and potable tap water of good quality is generally acceptable.

Identification of Chemicals

The practices generally followed in the technical literature on metallography are used to identify the chemicals utilized in the preparation of etchants.

Aqueous Acids. In identification of aqueous acids, the name or formula alone, sometimes followed by "conc" or "concentrated," refers to the common commercially available concentrated laboratory grade (Table 1). Where more than one concentration is commonly available, the percentage by weight of the active constituent is shown after the name or formula.

Table 1 Characteristics of aqueous liquid chemicals used in many metallographic etchants

Except for sulfuric acid, all data apply to both laboratory and technical or commercial grades of chemicals.

Name	Active constituent	Nominal composition[a], wt%	Specific gravity	Degrees Baumé[b]
Aqueous acids				
Acetic acid, glacial	$HC_2H_3O_2$	99.5	1.05	7.0
Fluoboric acid	HBF_4	48	1.32	35
Hydrochloric acid[c]	HCl	37	1.18	22
Hydrofluoric acid	HF	48	1.15	19
Lactic acid	$HC_3H_5O_3$	85	1.20	24
Nitric acid	HNO_3	70	1.42	43
Perchloric acid	$HClO_4$	70	1.67	58
		60	1.53	50
Phosphoric acid (ortho)	H_3PO_4	85	1.70	60
Sulfuric acid	H_2SO_4	96[d]	1.84[e]	66[e]
Miscellaneous aqueous chemicals				
Ammonium hydroxide	NH_4OH	28[f]	0.90	26
Hydrogen peroxide	H_2O_2	3[g]	1.01	1.4
		30[h]	1.11	15

(a)	Nominal percentage of the active constituent: remainder is water. Reagents made by different manufacturers may differ slightly in nominal concentration and allowable range of concentration.
(b)	Specific gravity as indicated on the Baumé scale: sometimes used for technical grades and in laboratory measurements.
(c)	Technical grade is also called muriatic acid.
(d)	Laboratory grade. Technical grade has concentration of 93%.
(e)	Specific gravity and degrees Baumé are nearly constant for 93 to 100% sulfuric acid.
(f)	Percent NH_3.
(g)	Sometimes called "10 volume."
(h)	Sometimes called "100 volume."
(i)	Sometimes called "170 volume."

Where an acid is designated as "tech," the technical grade that has the same concentration as the common laboratory grade is meant. The concentration of technical grades is sometimes expressed by suppliers in terms of specific gravity or degrees Baumé (°Bé), as shown in Table 1. Most technical-grade chemicals are available in several different concentrations.

Miscellaneous Aqueous Chemicals. A variety of aqueous chemicals, such as ammonium hydroxide and hydrogen peroxide (Table 1), which are used in various etchants, are identified similarly to aqueous acids. Concentration must always be specified for hydrogen peroxide, which is available in several widely differing concentrations.

Alcohols. The alcohols most frequently used in etchants are methanol and ethanol (Table 2). It is important to use alcohol that has the desired water content (anhydrous or 95% alcohol, whichever is specified) in etchants that contain only a small percentage of water.

Table 2 Characteristics of pure methanol and ethanol

Name	Active constituent	Nominal composition[a], vol%
Methanol (methyl alcohol)	CH_3OH	99.5[b]
Methanol (methyl alcohol), 95%	CH_3OH	95[c]
Ethanol (ethyl alcohol), anhydrous	C_2H_5OH	99.5[d][e]
Ethanol (ethyl alcohol), 95%	C_2H_5OH	95[e]

(a) Nominal percentage of the active constituent: remainder is water unless otherwise specified.

(b) Synthetic methanol: the commercial grade is of high purity and is satisfactory for use in all ordinary metallographic etchants where methanol is specified (wood alcohol has not been manufactured commercially in the United States since 1969). Methanol is available only as an anhydrous (also called absolute) grade containing less than 0.1 or 0.2% water as packaged, and usually not more than about 0.5% water at time of use, depending on storage and handling.

(c) Where methanol, 95%, is called for, the ordinary anhydrous grade must be diluted by the user with 5% water by volume.

(d) The anhydrous (also called absolute) grade of ethanol is ordinarily used only where no significant amount of water can be tolerated. It contains less than 0.1 or 0.2% water as packaged, and usually not more than about 0.5% water at time of use, depending on storage and handling.

(e) Available only with special government permit

Practice with regard to the substitution of methanol for ethanol, or vice versa, and with regard to the use of some grades of denatured ethanol in etchants, varies greatly among metallographic laboratories. In most alcoholic etchants, ethanol can be substituted for methanol. This substitution is desirable, because methanol is a cumulative poison, while ethanol is not. Safety considerations may rule out alcohol substitutions in accepted formulations for electropolishing without a thorough chemical study. Also, ethanol should not be substituted for methanol in nital containing more than 3% by volume of concentrated nitric acid. In addition, it should not be substituted in other methanol-based etchants that contain strong oxidants and only a small percentage of water (if they are being stored in tightly stoppered bottles) due to possible pressure buildup and explosion. Mix these ingredients fresh and do not store them. *Never* store mixtures based on higher-order alcohols.

In a wide variety of applications for which the etchant is specified to contain ethanol (excluding electropolishing electrolytes), a number of laboratories have found it convenient and satisfactory to substitute for pure "anhydrous" or "absolute" (99.5%) ethanol and for pure 95% ethanol (Table 2), either a proprietary solvent or denatured "reagent" alcohol having a suitable water content (as shown in the lower part of Table 3), which are available without permit from suppliers of laboratory chemicals. These grades have been formulated in accordance with U.S. government regulations to be suitable for general laboratory purposes and have been denatured with small percentages of volatile solvents; they may be substituted for pure ethanol having the same water content, except where pure ethanol is required for some special reason.

Table 3 Nominal compositions of various grades of denatured alcohol (ethanol) used in some metallographic etchants

See text for discussion of suitability of the various grades for use in etchants.

Component	Parts by volume in specially denatured alcohol[a]					
	Formula SD-1[b]		**Formula SD-3A**		**Formula SD-30**	
	Anhydrous	**95%[c]**	**Anhydrous**	**95%[c]**	**Anhydrous**	**95%[c]**
Ethanol, anhydrous	100	95	100	95	100	95
Water	. . .	5	. . .	5	. . .	5
Methanol	4	4	5	5	10	10
Methyl isobutyl ketone	1	1	. . .	. . .	. . .	. . .

Component	Parts by volume in proprietary solvent[d]		Parts by volume in "reagent" alcohol[d]	
	Anhydrous	**95%[c]**	**Anhydrous**	**95%[c]**
SD-1 anhydrous[b]	100	. . .	. . .	. . .
SD-1, 95%[b][c]	. . .	100	. . .	. . .
SD-3A, anhydrous	. . .	. . .	95	. . .
SD-3A, 95%[c]	. . .	. . .	. . .	95
Methyl isobutyl ketone	1	1	. . .	. . .
Hydrocarbon solvent or gasoline	1	1	. . .	. . .
Ethyl acetate	1	1	. . .	. . .

(a) Specially denatured alcohol is available only with special government permit.

(b) The formula shown here has replaced the old SD-1 formula in which wood alcohol was specified: wood alcohol has not been manufactured commercially in the United States since 1969.

(c) The designation of type of denatured alcohol as "95%" means that the denatured product contains 5 parts of water for every 95 parts of anhydrous (absolute) ethanol, plus denaturants as specified.

(d) Available without government permit from suppliers of laboratory chemicals, for scientific and general laboratory purposes.

The specially denatured (SD) alcohols described in Table 3 are generally suitable for use in etchants. However, SD alcohol is obtainable only with special government permits and usually can be purchased only in larger quantities than the proprietary solvent and "reagent" alcohol in Table 3, and only from major suppliers of solvents.

Water of Hydration. With some exceptions, it has been common practice since the earliest days of metallography to identify solid salts and acids used in etchants only by names and abbreviated formulas, without showing the presence or absence of water of hydration. Historically, in developing and preparing etchants, the most stable hydrate (which was the common commercial form) was ordinarily used, except for salts that do not form hydrates. Current practice varies from laboratory to laboratory.

Using the specified amount of either the anhydrous or a hydrated form of a solid salt or acid in preparing an etchant will in most cases produce essentially the same etching behavior. Any difference in results will usually be small in comparison with the effects of normal differences in technique and other variables in specimen preparation. Exceptions are the preparation of etchants that must be anhydrous or must contain only a small and fairly critical percentage of water for proper etching activity; for such etchants, the need to use specific anhydrous or hydrated forms of each component should be clearly stated.

Some salts (such as ferric nitrate) do not exist in an anhydrous form. Conversely, some nominally water-free compounds contain a substantial percentage of water. One of these is picric acid, for which the 10 to 15% water content found in laboratory grades is necessary for satisfactory performance of etchants based on it (Table 4). Always keep picric acid moist to eliminate the possibility of explosion.

Table 4 Descriptions of miscellaneous chemicals used in metallographic etchants

aluminum chloride, anhydrous. **Solid; $AlCl_3$; reacts violently with water, evolving HCl gas; use of hydrated form, $AlCl_3 \cdot 6H_2O$, is preferred.**
ammonium molybdate. **Crystals; also called ammonium paramolybdate or heptamolybdate; $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$; can be used interchangeably with *molybdic acid, 85%.***
benzalkonium chloride. **Crystals; essentially alkyldimethyl-benzyl-ammonium chloride. May not be readily available in this form; see *zephiran chloride.***
1-butanol. **See *n-butyl alcohol.***
2-butoxyethanol. **See *butyl cellosolve.***
n-butyl alcohol. **Liquid; normal butyl alcohol; also called butyl alcohol and 1-butanol.**
butyl carbitol. **Liquid; diethylene glycol monobutyl ether.**
butyl cellosolve. **Liquid; ethylene glycol monobutyl ether; also called 2-butoxyethanol.**
carbitol. **Liquid; diethylene glycol monoethyl ether.**
cellosolve. **Liquid; ethylene glycol monoethyl ether.**
chromic acid. **Dark-red crystals or flakes; CrO_3; also called chromic anhydride, chromic acid anhydride, and chromium trioxide. (See *chromic oxide,* Cr_2O_3.)**
chromic anhydride. **See *chromic acid.***
chromic oxide. **Fine green powder; Cr_2O_3; a polishing abrasive. Do not confuse with *chromic acid* (CrO_3), which is a strong acid and a component of many etchants.**
cupric ammonium chloride. **Crystals; a double salt, $CuCl_2 \cdot 2NH_4Cl \cdot 2H_2O$. If not available, substitute 0.6 g $CuCl_2 \cdot 2H_2O$ plus 0.4 g NH_4Cl for each gram of the double salt.**
diethylene glycol. **Syrupy liquid; also called 2.2'-oxydiethanol and dihydroxydiethyl ether; $(HOCH_2CH_2)_2O$. More viscous than ethylene glycol; otherwise similar in behavior.**
diethylene glycol monobutyl ether. **See *butyl carbitol.***
diethylene glycol monoethyl ether. **See *carbitol.***
diethyl ether. **See *ether.***
ether. **Liquid; also called ethyl ether and diethyl ether; very low flash point, highly explosive; boiling point is 34.4 °C (94 °F).**
ethylene glycol. **Syrupy liquid; also called 1,2-ethanediol and dihydroxyethane; $(CH_2)_2/(OH)_2$. Less viscous than diethylene glycol; otherwise similar in behavior.**
ethylene glycol monobutyl ether. **Liquid; also called 2-butoxyethanol or butyl cellosolve.**
ethylene glycol monoethyl ether. **See *cellosolve.***
ethyl ether. **See *ether.***
ferric nitrate. **Crystals; $Fe(NO_3)_3 \cdot 9H_2O$. There is no anhydrous form of this salt.**
fluoboric acid, 48%. **Liquid; HBF_4; if not readily available in small quantities, substitute 10.3 mL HF (48%) plus 4.4 g H_3BO_3 for each 10 mL of 48% fluoboric acid specified.**
glycerol. **Syrupy liquid; also called glycerin or glycerine; $C_3H_5(OH)_3$; contains up to 5% (by weight) water.**
molybdic acid, 85%. **Crystals or powder containing the equivalent of 85% MoO_3. This misnamed chemical consists mostly of ammonium molybdate (or paramolybdate), which is $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$. The two chemicals can be used interchangeably. See *ammonium molybdate.***
muriatic acid. **Liquid; technical grade HCl (see Table 1).**
picric acid. **Crystals; 2,4,6-trinitrophenol; crystals of laboratory chemical contain 10 to 15% water; explosive; its crystalline metallic salts are even more explosive. Do not use grades that do not have the 10 to 15% water content.**
pyrophosphoric acid. **Crystals or viscous liquid; $H_4P_2O_7$, anhydrous; hydrolyzes to phosphoric acid (H_3PO_4) slowly in cold water and rapidly in hot water.**
zephiran chloride. **Aqueous solution; a proprietary material produced in grades containing about 12% and 17% (by weight) benzalkonium chloride (alkyldimethyl-benzyl-ammonium chloride) as the active constituent, plus some ammonium acetate; also called sephiran chloride. Available from pharmacies or pharmaceutical distributors. See *benzalkonium chloride.***

Miscellaneous Chemicals. Correct identification may present problems because of similarity in names of different chemicals or because of misleading or nonstandard nomenclature and trade names (Table 4). Also included are certain chemicals for which some aspects of composition or behavior are important.

Metallographic Practices Generally Applicable to All Metals

Safety Precautions

All chemicals are potentially dangerous and persons formulating and using etchants should be thoroughly familiar with the chemicals involved, and with the proper procedures for handling and mixing them. The discussion that follows indicates many of the potential hazards that attend the use of chemicals and describes precautions and safe practice for averting these hazards.

Ventilation. All mixing, handling, and use of etchants should be done in a well-ventilated area, preferably within an exhaust hood, to prevent exposure to, or inhalation of, toxic and corrosive fumes. Use of an exhaust hood is mandatory whenever large quantities of chemicals are handled or large areas of metal are etched (as in macroetching), and when carrying out lengthy electropolishing operations or electropolishing large areas. Special hoods are available for work with perchloric acid.

Protection of Personnel. When chemicals and etchants are being poured, mixed, or handled, and when etchants are being used, suitable protective equipment and clothing (glasses, face shield, gloves, apron, and other items, as appropriate) should always be worn, to prevent contact of chemicals with the eyes, skin, or clothing.

If chemicals contact the skin, they should be washed off promptly with water and soap. Medical attention should be obtained as soon as possible for chemical burns, especially if there are cuts or abrasions in the skin. If chemicals contact the eyes, the eyes should be flushed at once with large quantities of water, and medical attention should be obtained without delay. A face-and-eye fountain should be available for use wherever chemicals or etchants are stored or handled. Wherever quantities large enough to be hazardous are stored or handled, a safety shower is needed also. This washing equipment should be readily available and should be tested at scheduled intervals to ensure dependable performance in an emergency.

Hydrofluoric and fluosilicic acids can cause painful and serious ulcers on contacting the skin, unless washed off immediately. Also especially harmful to the skin are concentrated HNO_3, H_2SO_4, CrO_3, H_2O_2 (30 or 50%), NaOH, KOH, Br_2, and anhydrous $AlCl_3$. Inhalation of vapors or mist from these chemicals or etchants containing them can also cause irritation or serious damage to the respiratory system.

Container Material and Design. In preparing, storing, and handling etchants, use containers and equipment made of materials suitable for the chemicals used. Glass is resistant to nearly all chemicals. Polyethylene, polypropylene, and similarly inert plastics are resistant to hydrofluoric, fluosilicic, and fluoboric acids, unlike glass, as well as to solutions containing salts of these acids. These inert plastics are also recommended for prolonged storage of strongly alkaline solutions and strong solutions of phosphoric acid, both of which attack glass (especially, ordinary grades of glass).

Certain mixtures of chemicals can generate gaseous reaction products over a period of time or if inadvertently exposed to heat, and can build up dangerous pressures if stored in tightly sealed containers. The use of vented or pressure-relief types of stoppers instead of tightly sealed screw caps or conventional stoppers on bottles of etchants that are prepared in quantity and stored is a worthwhile safety precaution.

Heat Evolution in Preparing Etchants. Exercise caution and follow accepted laboratory procedures when mixing chemicals. In general, heat is evolved, sometimes in large amounts, when strong acids (particularly H_2SO_4), alkalis (NaOH and KOH), anhydrous $AlCl_3$, or their concentrated solutions are added to water, alcohols, or solutions of other chemicals, and when combining acidic with alkaline substances or solutions.

The acid, alkali, or anhydrous $AlCl_3$ should be introduced slowly to the water, alcohol, or solution, while stirring continuously to avoid local overheating. Incomplete mixing can permit layering, with danger of a delayed violent reaction. Special attention and special cooling procedures may be needed when large quantities of etchants are prepared and large areas of metal are etched, as in some macroetching, and when high currents are used in electropolishing.

Mixing of Oxidizing Agents with Reducing Agents. Exercise special care in mixing oxidizing agents (HNO_3, H_2SO_4, $HClO_4$, CrO_3, salts of these acids, persulfates, Br_2, and H_2O_2) with reducing agents (alcohols and other organic solvents, acetic acid, acetic anhydride, and most organic compounds); failure to follow accepted safe procedures can result in violent or explosive reactions. Acetic anhydride cannot be used safely in electropolishing solutions except in limited ranges of composition and water content, and its use is not recommended.

Care with Cyanides. The use of etchants that contain cyanides presents special toxicity hazards, because poisoning can result from inhaling hard-to-detect small amounts of HCN gas evolved from acidic solutions, from ingesting small amounts of cyanides, and from absorbing cyanides through the skin or exposed body tissues. Careful handling and the use of an effective exhaust hood are especially important. Used cyanide-containing solutions should be made slightly alkaline with ammonia and poured into a chemically resistant waste-disposal drain, and the drain flushed thoroughly with a copious amount of water.

Disposal of Etchants. Spent etchant solutions should be discarded individually promptly after use. They should be poured slowly into a chemically resistant waste-disposal drain in an exhaust hood, while at the same time running a substantial flow of tap water down the drain, after which the drain should be flushed thoroughly with a copious amount of water. Strongly acidic, strongly alkaline, corrosive, or toxic solutions should be handled with extra care when being disposed, because of the hazards described in the section "Protection of Personnel."

Special attention should be given to the safe discarding of used solutions that contain substantial amounts of volatile solvents, so as to avoid the creation of toxicity, fire, or explosion hazards from vapors of the solvents. Procedures for safe disposal of etchants may be controlled by local regulations that may vary substantially by location.

Metallographic Technique for Ferrous Metals

Edited by George F. Vander Voort, Buehler Ltd.

Technique for Carbon and Alloy Steels

THE PREPARATION OF SPECIMENS of carbon and alloy steels can require special consideration, and these special procedures are discussed in this article. However, procedures described in the section "Metallographic Methods" in the article "Metallographic Practices Generally Applicable to All Metals" regarding sectioning and polishing of specimens are, for the most part, applicable to carbon and alloy steels.

Sectioning

Proper sectioning of the surface to be examined is a very important step in preparing steel specimens, because in this step, the metallurgical structure of the specimen can easily be altered. Care in sectioning is necessary for all steels, but it is especially necessary for fully hardened (untempered) steels. Precautions against overheating and excessive mechanical deformation of the steel during sectioning are mandatory.

The first step in preventing damage to the metallurgical structure is to minimize the amount of sectioning that is done. Regardless of whether the test pieces are separate pieces or are coupons attached to forgings or castings, they should be designed, whenever possible, to require a minimum amount of sectioning.

Abrasive-wheel cutting is the preferred method for sectioning of specimens. It is the required method for sectioning hardened steels, and it is a convenient method for sectioning all steels. Abrasive-wheel sectioning produces less damage to the structure and yields a smoother surface than band sawing or power hack sawing (techniques generally limited to steels below 35 HRC). When the specimen must be removed from a large mass of material, sectioning by sawing (provided that the steel is not too hard for sawing) usually precedes cutting with an abrasive wheel.

Rubber-bonded aluminum oxide wheels 52.5 mm (0.10 in.) thick are recommended. To minimize damage to the specimen, select a grade of cutoff wheel designed for the hardness of the steel being cut. For cutting hardened steels, a relatively softly bonded wheel is preferred.

Heating can be minimized by directing an ample flow of water containing a water-soluble oil over the surface being cut. The water-soluble oil helps protect the saw from corrosion and should always be used.

Separate Test Pieces. Because a major use of metallography is process control (for example, control of heat treating processes), separate test pieces are commonly used. They must have the same composition and thermal history as the steel for which the tests are run. A single test piece often suffices as a tensile-test bar and as a metallographic specimen. The size and design of the test piece depend largely on which tests are planned. When the test piece is to be used only for metallography, it is usually designed so that it can be cut into two or more small specimens.

Figure 1 shows two types of test pieces used for monitoring of heat treating processes. The solid, button-type test piece (Fig. 1a) is easy to prepare and is usually adequate. The washer-type test piece (Fig. 1b) has two advantages over the solid, button type. First, the washer-type piece can be more easily hung or otherwise secured in various locations of a heat treating furnace. Second, when it is sectioned, inside edges, which are less susceptible to edge rounding during grinding and polishing, are available for examination. To produce metallographic specimens, the test pieces are cut slightly off center so that a full half is available, and further specimen cutting proceeds (Fig. 2). Better edge retention is obtained if a compression mounting compound is used followed by a contemporary preparation practice.

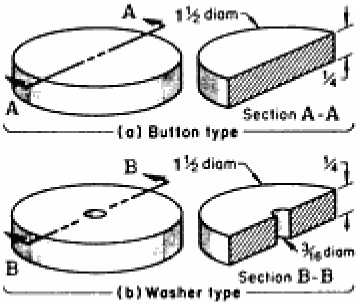
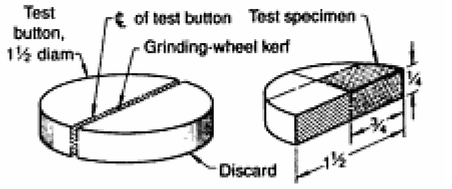
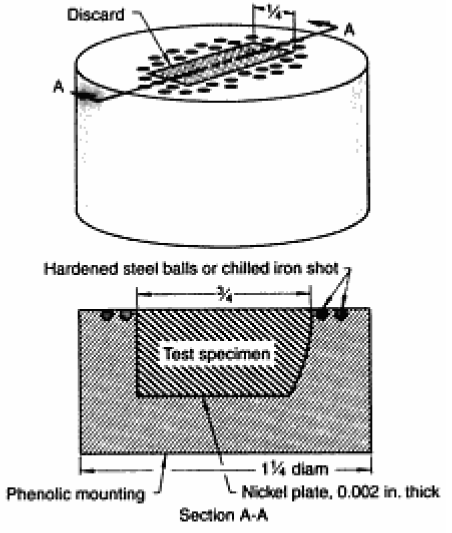

A
1½ diam
¼
A
Section A-A
(a) Button type
B
1½ diam
¼
$^3/_{16}$ diam
B
Section B-B
(b) Washer type

Fig. 1 Two types of test pieces used for metallographic monitoring of heat treatment processes. Dimensions are in inches.


Test button, 1½ diam
℄ of test button
Grinding-wheel kerf
Test specimen
¼
¾
1½
Discard

(a) Test button as cut to obtain specimen


Discard
¼
A
A
Hardened steel balls or chilled iron shot
¾
Test specimen
1¼ diam
Phenolic mounting
Nickel plate, 0.002 in. thick
Section A-A

(b) Test specimen mounted in phenolic

Fig. 2 Method of (a) cutting a test specimen from a test button and (b) mounting the test specimen to retain flatness for metallographic examination. Dimensions are in inches.

Mounting

A thermosetting phenolic resin is commonly used for mounting steel specimens. Phenolics are inexpensive and offer the advantages of quick mounting and reasonable hardness; the latter helps maintain flatness of the specimen during grinding and polishing. A disadvantage of phenolics is their thermosetting curing temperature (135 to 150 °C, or 275 to 300 °F); some steel specimens must not be heated in this range because it will affect their microstructure. Temperature control of the process is essential when specimens are mounted in phenolic, and some steels (for example, untempered tool steels) cannot be mounted in phenolic. Another disadvantage is that fragile specimens may be damaged by the pressure required during preparation of the mount. Phenolic, by itself, may not provide adequate support for edge retention. Phenolics give adequate edge protection when cured in a press that maintains the mount under pressure during cooling back to ambient temperatures and when automatic preparation devices are used. Under other conditions, edge rounding may occur in varying degrees.

Powdered epoxy is an improved thermosetting mounting product. The required time, temperature, and pressure of mounting are similar to those for phenolics, but they produce a superior mount with better edge retention. Phenolics are badly degraded by hot etchants, while thermosetting epoxy holds up well.

Plastics that cure at room temperature, such as acrylics, polyesters, and epoxy resins, are preferred by some metallographers. Because use of these mounting materials involves casting, many molds can be poured at one time. Room-temperature curing plastics usually require several hours (or overnight) to set; however, some formulations, set in 1 to 2 h, depending on the amount of hardener used. Such mounts are usually fairly soft and thus require the same special techniques for edge retention as those used for thermoplastic materials. Care must be taken in mounting large specimens with castable epoxy. In some cases, high temperatures can be generated, resulting in cracking of the mount. Acrylics provide the shortest curing times, generally less than 10 min but do not provide good edge retention. They are less expensive than epoxies.

Mounting Techniques. The specific technique used for mounting carbon and alloy steel specimens depends on the magnification to be used, requirements for edge preservation, and mounting material. When examination will be made at no more than 100×, edges are of no particular interest, the maximum temperature incurred in mounting is not a problem, no special measures are necessary, and all mounting materials discussed are satisfactory. In contrast, when a magnification of more than 100× will be used and when edge preservation is of prime concern (especially when one of the softer mounting materials must be used), the mounting procedure must be carefully planned and special techniques may be required.

Plating the test piece with nickel is common practice. The nickel plate protects and preserves the edges during final cutting and helps maintain flatness during grinding and polishing. Electroless nickel plating solutions are commonly used. A plating thickness of about 5 to 10 μm (0.0002 to 0.0004 in.) is usually sufficient. It is best to hot compression mount electroless nickel-plated specimens using a press that cools the specimen to ambient temperature under pressure as hot ejection and rapid cooling often causes the plating to separate from the specimen, which greatly lessens it ability to protect the edge.

Another common practice, but less effective in obtaining and maintaining maximum flatness, is shown in Fig. 2. In this practice, a test button, such as that shown in Fig. 1, is sectioned by first cutting slightly off center and then cutting off a 19 by 6.4 mm ($\frac{3}{4}$ by $\frac{1}{4}$ in.) specimen, as shown at the right in Fig. 2(a). The specimen is mounted in phenolic ready for grinding and polishing (Fig. 2b). The mount features the use of hard metal pieces surrounding the specimen (Fig. 2b). Often, these are small hardened steel balls, but chilled iron shot costs less and is equally satisfactory for most purposes. Alumina pellets have also been used, but these greatly reduce the grinding and polishing rates. Another alternative is to surround the specimen with a pipe section. For the specimen shown in Fig. 2, the inside diameter of the pipe section would have to be about 22 mm ($\frac{7}{8}$ in.). These techniques are less effective than plating, and there is no guarantee that they will improve edge retention as much as needed.

Grinding and Polishing

Mechanical Grinding. In the traditional approach, steel specimens are ground using a series of progressively finer abrasive papers, for example, 120, 240, 320, 400, and 600 grit SiC using water as a coolant. Stationary or rotating (300 rpm) wheels are used. Grinding times are 60 to 120 s with the direction of grinding changed after each paper. SiC paper has a short life and is not reusable. Coarse, waterproof aluminum oxide paper is now available for rough (planar) grinding, and its life is substantially greater than that of standard SiC paper.

Mechanical Polishing. In the traditional method, polishing is broken into two steps, rough and fine with one or two different abrasive sizes being used in each stage. For rough polishing, a napless cloth impregnated with diamond paste is preferred. Nylon, silk, thin cotton, canvas, and cotton drill cloth are traditionally used. Polishing with 6 μm diamond paste usually is sufficient, but some metallographers prefer to polish with 9 μm followed by 3 μm paste or to use 6 and 1 μm or 3 and 1 μm diamond.

Powdered alpha alumina (Al_2O_3) in the same range of sizes as diamond can be substituted for diamond paste, but diamond is a much more efficient abrasive. Rough polishing is most often done on a cloth-covered disk rotating at 150 rpm. The specimen is held by hand and moved in the direction opposite to the direction of wheel rotation. Alternatively, automatic devices can be used for grinding and polishing. Fine polishing is traditionally done on a napped cloth with a slurry of gamma alumina and water. Almost any soft cloth can be used, but the most satisfactory is one with synthetic fibers on a cotton backing. Alumina in a 0.05 μm size is used most often, although some metallographers prefer to fine polish in two steps--first with 0.3 μm and then with 0.05 μm alumina. Wheel speed and specimen rotation for fine polishing are the same as for rough polishing. Time required for rough and fine polishing varies with hardness and size of the specimen, but the average time is 60 to 120 s per step, using the technique previously described.

Contemporary Procedures. The increased use of automated polishing devices has fostered the adoption of more efficient, improved preparation procedures designed to reveal the true structure ("specimen integrity" concept). If an automated system is used with a specimen holder that accommodates a number of specimens (which varies with size and format, i.e., 8 or 12 in. wheel size), mounted or unmounted, and if the pressure is applied centrally, then the first step of grinding must remove the damage introduced by sectioning and make all of the specimens coplanar. This step is often called "planar grinding." If the force is applied to each specimen individually (most practical with mounted specimens), then the first step of grinding is used to remove sectioning damage as the specimens are not rigidly constrained in the holder. The application of force to each individual specimen seats each specimen independently of the others. In grinding or polishing, the head can rotate in either the same direction as the platen (complementary) or in the opposite direction to the platen (contra). Contra rotation is more aggressive than complementary, and thus produces a higher removal rate, but this does not always produce better results. Complementary rotation is safer to use. For final polishing, contra rotation is helpful in that the polishing slurry is not swept off the surface as readily as with complementary rotation.

Numerous surfaces can be used for the rough grinding or planar grinding step depending upon the equipment available and the nature of the work. For planar grinding, a high speed grinder using a coarse grit aluminum oxide stone commonly has been used. This setup produces fast, efficient removal of sectioning damage. However, it requires purchase of an expensive single-purpose machine. Grinding stones are expensive; their surface must be trued with a diamond tool before each use, and the stone creates a significant depth of damage.

If the specimen has been cut using the proper abrasive wheel, then the depth of damage and the roughness of the cut are substantially less than from band sawing or power hack sawing. In such a case, a relatively fine abrasive can be employed to remove the sectioning damage. Going to a stone is a step back to a much coarser grit than needed. Wafering blades or thin abrasive cutoff wheels produce even less damage than a standard abrasive wheel. If the grinding/polishing machine has individual force ability, then the starting grinding surface can be equivalent to 240 or 320 grit SiC paper.

Obviously, ordinary SiC abrasive (waterproof) paper can be used for the first grinding step. Waterproof aluminum oxide abrasive papers are also highly effective. Other surfaces are also possible, such as lapping platens, rigid grinding disks, and metal-bonded or resin-bonded diamond disks, depending upon the material being prepared. These procedures yield extremely good surface flatness.

Modern preparation practices are designed to yield acceptable surfaces (for the application) with a minimum number of steps. For carbon and alloy steels, and for most other steels, four or five step practices are possible. After the initial grinding step, several options are possible involving platens, rigid grinding disks, or napless, heavy polyester cloths. The latter is the most universal in application and the best choice for low to medium hardness carbon and alloy steels. Rigid grinding disks may be ineffective at removing deformation from ferrite. In general, the heavy napless woven polyester cloths are used with 15 or 9 μm diamond slurries (either polycrystalline or monocrystalline synthetic diamond) as these are easiest to add while the machine is running. Coarse polishing times of about 5 min are common.

In the next step, a hard, synthetic chemotextile cloth is generally used with a 3 μm diamond slurry for 3 to 5 min. This is followed by a 1 μm diamond slurry on a hard, napless cloth (acetate is often used) for 2 to 3 min. This step is often optional; some prefer to skip this step and go to final polishing with alumina or colloidal silica. At this point, the amount of residual damage in the specimen is very low. The inclusions are fully retained, and the edge is flat and can be examined with ease at 500× or above. Etching may bring out a few minor scratches that are well within the level that can be tolerated in production metallography.

If publication-quality micrographs are needed, an extra step can be added to completely eliminate any remaining deformation or scratches. Vibratory polishing using colloidal silica, acidic alumina suspensions, or with neutral alumina suspensions produces the highest quality results. However, these abrasives can be used nearly as effectively on a rotating wheel covered by a suitable cloth. If edge preservation is required, a short nap cloth, such as those recommended for use with colloidal silica, should be used. If edge preservation is not critical, then a somewhat softer, medium-nap cloth, such as the popular synthetic suede cloths can be used.

Electrolytic polishing has limited application to carbon and alloys steels because it removes inclusions, severely rounds edges, and results in preferential attack in multiphase systems. Electropolishing has the advantage of speed: a high-quality polish that will reveal ferritic grain size can be obtained in about 2 min. In most instances, it is not necessary to mount the specimen for electrolytic polishing, although a conductive mount can be used.

Etching

Compositions of etchants used for microscopic examination of carbon and alloy steels are given in Table 1. Table 1 also lists the major characteristics of microstructures that each etchant reveals. Nital is by far the most widely used etchant for carbon and alloy steels.

Table 1 Etchants for microscopic examination of carbon and alloy steels

No.	Etchant	Purpose, or characteristic revealed
1	Nital: 1 to 5 mL HNO_3 in 99 to 95 mL ethanol (95%) or methanol (95%)	Develops ferrite grain boundaries in low-carbon steels; produces contrast between pearlite and a cementite or ferrite network; develops ferrite boundaries in structures consisting of martensite and ferrite; etches chromium-bearing low-alloy steels resistant to action of picral. Preferred for martensitic structures.
2	Picral: 4 g picric acid in 100 mL ethanol (95%) or methanol (95%)	Reveals maximum detail in pearlite, spheroidized carbide structures, and bainite; reveals undissolved carbide particles in martensite; differentiates ferrite, martensite, and massive carbide by coloration; differentiates bainite and fine pearlite; reveals carbide particles in grain boundaries of low-carbon steel. Addition of about 0.5 to 1 mL zephiran chloride wetting agent increases speed of attack.
3	Vilella's reagent: 5 mL HCl, 1 g picric acid, 100 mL ethanol (95%) or methanol (95%)	For contrast etching (a); may reveal prior austenite grains in tempered martensite and in austempered steels; reveals pearlite colonies.
4	1 to 1.5 mL HCl (conc), 2 to 4 g picric acid, 100 mL ethanol (95%)	Reveals pearlite colonies (b).
5	30 g $K_2Cr_2O_7$ in 225 mL hot distilled water; and 30 mL acetic acid (glacial)	Reveals lead inclusions, causing them to appear yellow or gold when specimen is examined under polarized light (c)
6	16 g CrO_3 in 145 mL distilled water; add 80 g NaOH (d)	Reveals intergranular oxidation due to overheating prior to hot working (e)
7	10 g potassium metabisulfite, 100 mL water	For resolution of hardened structures. Should be preceded by an etch in nital or picral.
8	Howarth's reagent: 10 mL H_2SO_4, 10 mL HNO_3, 80 mL water	For detection of overheating and burning, and for examination of steel forgings.
9	8 g sodium metabisulfite in 100 mL water	Produces good contrast in as-quenched martensitic structures
10	1 g KCN in 100 mL water, mixed with 0.25 g diphenylthiocarbazone in 10 mL chloroform	Reveals lead inclusions by coloring them red; coloration is most visible when specimens are viewed under polarized light.
11	Saturated aqueous picric acid plus 1 g/100 mL sodium tridecylbenzene sulfonate	Most successful etch for revealing prior austenite grain boundaries in medium- or high-carbon martensitic steels. Steels should be untempered, or tempered below 540 °C (1000 °F). Immerse or swab for up to 20 min.
12	2 g picric acid, 25g sodium hydroxide, 100 mL water	Alkaline sodium picrate. Use boiling for 30 s or more to darken cementite. Solution will attack mounts made from Bakelite.
13	50 mL cold saturated aqueous sodium thiosulfate, 1 g potassium metabisulfite	Klemm's tint etch; colors ferrite. Immerse for 40 to 100 s until surface is colored. A light pre-etch with nital or picral improves sharpness.

(a)	Specimen should be tempered for 20 to 30 min at 315 °C (600 °F).
(b)	Immerse specimen for 5 to 10 s in solution at room temperature.
(c)	Etch for 10 to 20 s in solution at room temperature, rinse in hot water and dry.

(d) Sodium hydroxide (NaOH) must be added slowly, with constant stirring.
(e) Immerse specimen in boiling solution for 10 to 30 min, rinse in hot water, dry in air blast.

Nital versus Picral. Although nital and picral are so similar in etching action that they are often regarded as being interchangeable, they differ in several important respects. For some structures, there may be little difference in etching action between nital and picral; for others, the difference is significant.

In general, picral is preferred when ferrite-carbide aggregates are to be examined. Nital, which is sensitive to crystal orientation, is preferred for revealing ferrite grain boundaries and for the study of martensitic structures. Picral does not reveal ferrite grain boundaries unless the specimen is overetched.

Special-Purpose Etchants. Addition of hydrochloric acid to picral (Vilella's reagent in Table 1) brings about radical changes in etching behavior. For medium-carbon alloy steels quenched and tempered between 315 and 480 °C (600 and 900 °F), Vilella's reagent may occasionally reveal the prior-austenite grain structure by producing grain contrast. The color differences between grains in a specimen result from deeper attack of some grains than of others (contrast etching). In general, large austenite grains are more sharply and clearly resolved than small ones.

The most successful etchant for revealing prior-austenite grain boundaries is saturated aqueous picric acid plus about 1 g/100 mL of a wetting agent (sodium tridecylbenzene sulfonate is the most popular wetting agent). This procedure works best on medium-carbon, high-carbon, and alloy steels in the as-quenched or tempered (up to about 540 °C, or 1000 °F) condition. The steel must contain $\geq 0.005\%$ P for this etchant to work. Etching may be done by immersion or swabbing for times up to about 20 min. Light repolishing to remove some of the structure etching helps to bring out the grain-boundary attack.

An etchant consisting of 8 g of sodium metabisulfite in 100 mL of water develops good contrast in as-quenched martensitic structures. Several other special-purpose etchants are listed in Table 1.

Macroetching of Carbon and Alloy Steels

Macroetching of carbon and alloy steels is an inspection procedure for revealing certain aspects of the quality and structure of a steel by subjecting it to the corrosive action of an etchant and examining it visually or at low magnification. Macroetching is widely used for inspection of bars, billets, forgings, castings, and other steel products. Specimens usually are selected to represent a given batch or lot of metal and are tested by etching in acid until the structural characteristics or conditions are revealed. ASTM E 381 describes the macroetch test procedure.

Equipment of Macroetching

The principal equipment for macroetching comprises a container for the etchant, provision for heating the etchant (if necessary), a ventilating system to contain and carry away corrosive fumes, and some means for washing and drying the specimen.

Etchants

Table 2 lists the etchants that are most commonly used for macroetching of carbon and alloy steels. A 50% solution composed of hydrochloric acid and water (etchant 1 in Table 2) is the most widely used macroetchant and is capable of revealing a number of characteristics in carbon and alloy steels (last column in Table 2). ASTM E 340 lists many macroetchants for steels as well as other metals.

Table 2 Etchants and recommendations for macroetching of carbon and alloy steels

Etchant		Etching time(b)	Surface required(c)	Purpose, or characteristic revealed
No.	**Composition (parts listed are by volume)(a)**			
Etchants for use 71 to 82 °C (160 to 180 °F)(b)				
1	1 part HCl, 1 part water	15 to 60 min	A or B	Segregation, porosity, hardness penetration, cracks, inclusions, dendrites, flow lines, soft spots, structure, weld examination
2	50 parts HCl, 7 parts H_2SO_4, 18 parts water	30 to 60 min	A	Same as for etchant 1
3	38 parts HCl, 12 parts H_2SO_4, 50 parts water	30 to 60 min	A or B	Same as for etchant 1
Etchants for use at room temperature				
4	2 to 25% HNO_3 in water or ethanol	1 to 30 min	B or C	Carburization and decarburization, hardness penetration, cracks, segregation, weld examination
5	2.5 g $CuCl_2 \cdot 2H_2O$, 20 g $MgCl_2 \cdot 6H_2O$, 10 mL HCl, 500 mL ethanol	Until coppery sheen appears	B or C	Phosphorus-rich areas, banding
6	50 g $(NH_4)_2S_2O_8$, 500 mL water	Swab until desired etch is obtained	C	Grain size, weld examination
7	40 g $FeCl_3$, 3 g $CuCl_2$, 40 mL HCl, 500 mL water	15 to 30 s	B or C	Dendritic structure of cast steel. (Precede use of this etchant with etch in 10% nital for 10 to 20 s.)
8	30 g $FeCl_3$, 1 g $CuCl_2$, 0.5 g $SnCl_2$, 50 mL HCl, 500 mL ethanol, 500 mL water	30 s to 2 min	C	Dendritic structure of cast steel. (Overetching deposits excessive copper, which may obscure details of structure.)
9	4 g picric acid in 100 mL methanol	3 to 5 h	C	Carbon segregation

(a) All acids listed are of concentrated strength; commercial grades ordinarily can be used instead of laboratory or reagent grades. Water or alcohol should never be poured into an acid; rather, the acid should always be poured and gradually stirred into the other liquid.

(b) See text for discussion of variations in time and temperature.

(c) A, saw-cut or machined surface; B, average ground surface; C, polished surface.

Etching Procedure

The usual procedure in macroetching is to put the prepared specimen directly into the etching solution, with the surface to be examined either face up or vertical to permit the gas generated to escape freely. Nonuniform etching will result if specimens are overlapped or are stacked too close together. When heated etchants are used, have the etching solution at the pre-established temperature before the specimens are immersed.

Temperature of Etchant. For the etchants in Table 2 used above room temperature, an etching temperature of 71 to 82 °C (160 to 180 °F) is recommended. At temperatures on the lower side of this range, the etching reaction is sufficiently vigorous to provide effective etching, and yet evaporation of the solution is not excessive. However, in production-control etching, temperatures on the higher side of the range are preferred, because they decrease the time of etching.

Time of etching depends on the type of steel, surface condition, and physical condition of the specimen. For best reproducibility of results with a large number of specimens, the time should be measured and should not vary from batch to batch. If the etching time is too short, all of the desired information may not be revealed.

Specimen Preservation. After a specimen has been properly etched, it should be removed from the etchant, rinsed thoroughly under running water, scrubbed with a stiff fiber brush to remove the deposit of "smut" from the surface, rinsed again, and dried by a warm-air blast or by blotting with paper or cloth towels. A cold-water rinse is used. Immersion in the etchant for a few minutes after scrubbing results in better definition, especially of flow lines.

As a temporary means of avoiding rust, the etched specimen may be rinsed in water, dipped in a dilute alkaline solution (e.g., aqueous ammonium hydroxide) to neutralize the remaining traces of acid, and washed in hot water. The residual acid can also be neutralized by dipping the specimen in a dilute solution of potassium carbonate or sodium carbonate; in addition to neutralizing the acid, these solutions also leave a film that prevents rust after drying.

Technique for Low-Carbon Steel Sheet

Complete examination of a specimen of low-carbon steel sheet requires at least three specimens: a longitudinal cross section, which runs parallel to the rolling direction; a transverse cross section, which runs perpendicular to the rolling direction, and a surface specimen taken parallel to the rolling plane and viewed perpendicular to the rolling direction.

Mounting

Mounting techniques for steel sheet specimens are basically the same as those described in the section "Metallographic Methods" in the article "Metallographic Practices Generally Applicable to All Metals." a thermosetting mounting material, such as a phenolic, is commonly used, although compression-mounting epoxy mounts provide much better edge retention. A mounting press that cools the specimen back to ambient under pressure enhances edge retention with any mounting material. When the microstructure is likely to be affected by the curing temperature of a phenolic (150 °C, or 300 °F), or when steel sheet specimens are so thin that they may be crushed or distorted by the mounting pressure, cold mounting or mechanical mounting may be used.

Clamp mounting is quite successful for holding steel sheet specimens during preparation. Sometimes this technique is used where no mounting press is available, but more often it is used where many specimens are being prepared or where speed of preparation is important. In clamp mounting, several specimens can be clamped in sandwich form between two plates (Fig. 3). Bleeding problems are eliminated if the clamp is tightened very securely. Some users insert thin spacers, generally plastic, between the specimens before tightening. Edge retention with clamps is excellent.

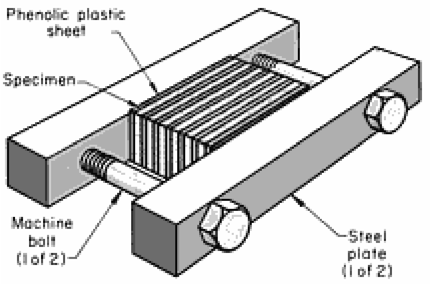


Fig. 3 Typical arrangement for clamp mounting of longitudinally or transversely oriented sheet steel sections

Technique for Coated Steel Sheet

Most techniques for preparing metallographic specimens of coated steel sheet are the same as those used for preparing specimens of uncoated steel sheet, with minor variations and precautions.

Galvanized Steel Sheet

Care in cutting galvanized steel sheet is necessary in order to avoid delamination of cut edges at the interface of the zinc coating and the steel backing. Cutting should be done with an abrasive wheel, rather than by shearing.

Aluminum-Coated Steel Sheet

Preparation of hot-dip aluminum-coated steel for metallographic study is similar to preparation of galvanized steel; both types of coating are quite soft. Staining is not a problem with aluminum-coated steel sheet, so water can be used as a suspending fluid and lubricant.

Stainless-Clad and Chromized Steel Sheet

Stainless-clad and chromized steel sheets, although manufactured by different processes, consist of a relatively soft low-carbon steel core sandwiched between stainless steel or chromium-rich surface layers. The surface layers are harder than the low-carbon steel base metal.

Porcelain Enameled Steel Sheet

Because of the brittleness of porcelain enamel coatings, cutting a specimen from porcelain enameled steel sheet requires the use of procedures that will minimize or prevent chipping of the friable coating. A thin alumina cutoff wheel or a diamond blade on a precision saw may be used. When the cutoff wheel is used, the cut should be made about 3 mm ($\frac{1}{8}$ in.) away from the area to be examined. The specimen is then mounted and ground back about 3 mm to remove areas damaged in cutting. Use of a precision diamond saw permits cutting directly adjacent to the area to be examined.

Mounting specimens of porcelain enameled steel sheet may present a problem, because they cannot be bent into "L" or "Z" shapes without damaging the coating. There are, however, several other techniques that may be used. Clamp mounting is applicable to porcelain enameled specimens and preferred in some laboratories. Another method for mounting several specimens simultaneously is to clip them together or to glue them together with an epoxy resin. The specimens may be interleaved with strips of plastic or soft metal, such as copper or lead. Either the clipping or the gluing technique will provide a section thickness sufficient to be self supporting when placed upright in a mold. Alternatively, plastic chips can be used to hold the specimen perpendicular. Castable resins, chiefly epoxy, are preferred for mounting.

Technique for Steel Plate, Tube, and Pipe

Steel tube and pipe do not present any special problems in specimen extraction; steel plate does. Because plate may be quite thick, it often is necessary to examine specimens from three or more locations in order to observe true conditions. Extraction of specimens from a thick plate is likely to require a considerable amount of cutting. Various machining methods, including sawing and hollow boring, are used to obtain the initial test pieces. During machining, care must be taken to prevent the specimen from becoming overheated, which might change the structure of the steel.

Examination of Welded Joints

Steel sheet, strip, plate, tube, and pipe are often welded; therefore, techniques for metallographic examination of welded joints are needed. Welds are usually examined at a low magnification so that a large area can be viewed. Specimens from weldments are sectioned, mounted, ground, and polished in the same manner as other metallographic specimens. Whenever possible, the specimen should contain the weld nugget, heat-affected zone, and a portion of the adjacent base metal.

Technique for Carbon and Alloy Steels of Medium Carbon Content

This group of steels is comprised of wrought steels that have carbon contents ranging from about 0.25 to 0.50%, and, for the alloy grades, total alloy contents up to about 7% (but mostly less than 3%). The methods of preparing metallographic specimens discussed in this article and in the article "Metallographic Practices Generally Applicable to All Metals" are generally applicable to carbon and alloy steels of medium carbon content. Many large forgings, because they are too costly to destroy or too difficult to section, are designed with an allowance of metal on the end from which test coupons can be taken, usually by sawing or hollow boring. Small forgings (up to about 5 lb) may be sectioned instead of being designed with test coupons. Test coupons are cut into specimens, usually by sawing or abrasive-wheel cutting. Often, specially designed test specimens are used.

Technique for Carbon and Alloy Steels of High Carbon Content

Heat treated, high-carbon steels are more sensitive to damage by abrasive cutting than low-carbon steels. A hardened high-carbon steel specimen should not be heated to more than 150 °C (300 °F) during cutting, and sometimes (for example, when the steel is to be examined in the as-quenched condition) the specimen should not be heated to more than about 66 °C (150 °F). Excessive heat will temper the martensite and change its appearance, and it could result in misinterpretation of the structure of the steel.

Abrasive cutting must always be done using a coolant (water containing a soluble oil) and a softly bonded wheel to prevent burning. Etching of the cut specimen in nital will reveal this condition and indicate the corrective measures that must be taken to bring out the original structure of the specimen, such as removal of more stock from the surface to be examined. Avoiding burning during cutting is a far better practice than trying to grind away burning damage.

Technique for Case Hardening Steels

NITRIDED STEELS require special preparation. Techniques described in the first part of this section are oriented primarily toward preparation of specimens from carburized and carbonitrided steels, although they are also applicable to preparation of specimens from cyanided steels.

Carburized Steel and Carbonitrided Steel

Most steels used for carburizing and carbonitriding have an initial carbon content ranging from 0.10 to 0.30%, and they may or may not contain one or more alloying elements. Sometimes, to satisfy special requirements, medium-carbon steels are carburized.

Because the carbon content of carburized steel may range from that of the uncarburized core (0.10 to 0.30% C) to as much as 1.20% C in the case, specimens are difficult to extract and prepare. Even for a steel that has been carburized but not hardened, the hardness varies considerably from surface to center of a cross section. When the carburized steel has been hardened, the hardness difference between the core and the outermost portion of the case may exceed 40 points on the HRC scale.

Sectioning. Separate small test pieces designed to minimize the amount of sectioning required are often used. If the production parts are very small, one or more of them are sectioned for metallographic study. When the specimen must be removed from a large mass of material, the same meticulous care must be used.

Mounting techniques and precautions used for specimens of high-carbon steels are applicable to specimens of carburized steel. Overheating of specimens must be avoided to prevent changes in structure. The use of cold mounting and wet grinding is required for examination for retained austenite.

Preservation of the edges of carburized cases is of the utmost importance. Edge preservation is easier when the surface hardness is high. A mounting press that cools the specimen to near room temperature under pressure virtually eliminates shrinkage gaps that lead to edge rounding. Harder epoxy compression mounting compounds further aid edge preservation. Automatic polishing devices and use of napless and low-nap cloths are important. Nickel plating provides the best possible edge protection but by itself may not be adequate.

Grinding and polishing techniques are the same as those described for specimens of other steels. Automated polishing devices are advisable when the hardness varies widely within a specimen providing even pressure and uniform removal. It is highly desirable to minimize polishing time. Because of the wide differences in hardness within a single specimen, some constituents may polish in relief, and flatness of the specimen may be destroyed. Frequently, specimens that have been over polished must be completely reworked to regain flatness. Use of low-nap polishing cloths will reduce this problem.

Etching. Nital is a general-purpose etchant for routine metallographic study. It is well suited for revealing case depth, retained austenite, carbide networks, and surface decarburization. Nital is preferred for examining the hardened surface region. Picral will reveal nonmartensitic phases very clearly but not martensitic regions (unless they are highly tempered). Picral is preferred for examining the transition region and the unhardened core region.

Nitrided Steels

Preparation of nitrided steel specimens to reveal the true microstructure requires more exacting techniques than are normally required. The extreme hardness differential between the case and the core (case hardness $\geq$900 HK) causes problems. Also, the nitride concentration at the surface (white layer), which often is the primary subject of metallographic examination, may be entirely destroyed by ordinary preparation techniques. This layer is extremely thin.

Test Pieces. The principal use of metallography for nitrided steels is quality control of production nitriding. Often, the workpieces being nitrided are too valuable to permit destructive testing, and so separate test pieces are prepared of the same steel with the same preliminary heat treatment as the workpieces.

Test pieces must be made with great care. In one recommended practice, bars of the same steel of convenient length and 41 mm ($1\frac{5}{8}$ in.) in diameter are quenched and tempered, unless they are already in the heat treated condition. They are then turned and ground to a diameter of 38 mm ($1\frac{1}{2}$ in) so as to remove any decarburization or carburization that may have occurred in the preliminary heat treatment. The ground surface should be no rougher than 0.13 μm (5 μin.). Next, the turned and ground bars are cut into slices about 6 mm ($\frac{1}{4}$ in.) thick. This step can be done with a lathe; an abrasive cutoff machine can be used if coolant is supplied copiously to prevent burning. A hole can be drilled in the completed test piece, permitting it to be hung in the furnace to prevent its being lost during nitriding.

Plating of nitrided test pieces prior to sectioning is the best practice for protection of the edges and preservation of the white layer. Plating must be done without blasting or severe etching. Nickel plating has proved best. The thickness of the deposit is not critical; 0.05 mm (0.002 in.) is sufficient. Chromium plating is unsatisfactory, because the plate does not adhere well to nitrided surfaces without an unacceptable amount of surface preparation. Copper, zinc, and cadmium plates are too soft.

Mounting of Specimens. Compression mounting epoxy is preferred for mounting specimens of nitrided steel. The mounting temperature does not affect nitriding steels. Placing chilled iron shot or hardened steel balls around the specimen can be used for preserving flatness of the specimen during manual grinding and polishing. These are unnecessary when automated preparation devices are used.

Grinding and polishing nitrided steel specimens is the same as grinding and polishing of other steel specimens. Napless and low-nap cloths are recommended for edge retention.

Etching. Common practice is to etch the polished specimen, immediately repolish very lightly (just enough to remove evidence of etching), and then etch again. Some metallographers continue this procedure for two or more cycles to ensure that all disturbed metal is removed and that the true structure is revealed. These practices are not needed if proper care is taken during grinding and polishing.

For routine examination, nitrided steel specimens are most often etched in nital--2% nital for microscopic examination and up to 5% nital for case-depth measurements at low magnification. Nital reveals the white layer, the depth of case, and the structure of nitrided alloy steels, such as AMS 6470, 4140, and H13.

Technique for Steel Castings

CARBON AND ALLOY STEEL CASTING specimens are prepared by the same techniques as those used for preparing specimens of wrought carbon and alloy steels of the same composition.

Extraction of Specimens

In a single steel casting, section thickness can vary from a fraction of an inch to many inches. These differences in section thickness will result in different cooling rates, and thus in different microstructures, within the casting. This difference is true both for as-cast and for heat treated castings. Therefore, for complete examination of a casting, several specimens may have to be extracted.

Steel castings, both as-cast and heat treated, are usually soft enough to permit sawing or hollow boring for initial extraction of test pieces, after which the oversize pieces are reduced to specimen size by abrasive-wheel cutting. If the casting is hard, abrasive-wheel cutting is used for all operations. Precautions must be taken to avoid overheating during cutting.

Mounting

Phenolic resins are often used for mounting specimens. The microstructures of most steel castings are not affected by the high thermosetting temperature of phenolics.

Grinding and Polishing

Preparation of cast steels is the same as for wrought steels except that the casting may contain porosity or microshrinkage cavities. If these holes are not filled by epoxy (or wax), bleeding problems will occur. It may be necessary to vacuum impregnate partially prepared specimens with epoxy to fill the voids on the specimen surface. Grinding and polishing media, etchant solutions, and water will enter these openings and must be removed, or they may impair examination--

especially when an inverted microscope is used. Ultrasonic cleaning followed by careful drying (a heat lamp or an oven may help) may suffice if the holes are not filled.

Etching

Nital is the etchant most often used for specimens from steel castings. As usual, it is preferred for martensitic structures. Nital is easier to remove from pores and cavities than picral. Picral sometimes is used for etching specimens from steel castings, especially those from castings with carbon contents of more than 0.30%. Carbide structures are resolved better with picral than with nital.

Technique for Cast Irons

THE PRESENCE OF GRAPHITE in gray, malleable, and ductile cast irons makes preparation of these metals more difficult than steels. The soft and friable nature of the graphite phase, in combination with the relatively hard matrix, presents difficulties during preparation not normally experienced with other ferrous metals. Techniques that will promote a scratch-free and distortion-free surface for the matrix may not retain the graphite so that it can be observed after preparation. Similarly, techniques for polishing soft and friable phases, such as graphite, do not easily lend themselves to successful preparation of the harder matrix. The peculiar friability of graphite in cast iron results in the phase being torn out wholly, or in part, leaving cavities that are either opened up or burnished over, depending on the preparation procedure adopted. As a result, the shape and size of the graphite may not be truly represented, and an accurate assessment of the microstructure cannot be made. To obtain a scratch-free and distortion-free matrix containing well-preserved and polished graphite, special preparation procedures specific to cast irons containing graphite have to be adopted. The preparation of white cast iron specimens does not have the limitations imposed by the presence of graphite and conventional techniques are used.

Sectioning

Specimens can be obtained from iron castings using conventional cutting techniques, such as mechanical hacksawing or abrasive wheel sectioning. Sawing produces a rough-cut face and deforms the base metal to a much greater extent than does abrasive cutting. When specimens are obtained by sawing, a lubricant should be used, and grinding must commence with coarser-grit SiC papers than would be needed if the specimens were obtained by abrasive cutting. In cutting of hard materials, such as white irons, it is necessary to use a cutoff machine employing thin, softly bonded aluminum oxide wheels, and overheating must be avoided. Cutting with copious water flow is recommended to minimize heat effects. Abrasive cutting is preferred to bandsawing as damage to the surface is much less and the surface is smoother. This facilitates subsequent grinding.

Mounting

Specimens that are difficult to handle should be mounted using the hot compression mounting technique. In many laboratories, it may be convenient to mount all specimens, and mounting is often essential if polishing is to be done on automatic equipment. A suitable thermosetting phenolic plastic should be used as the mounting medium. It should provide sufficient adhesion and edge support to the specimen and minimize the rounding of edges that results in loss of sharpness during examination when a modern mounting press is used (specimen cooled to near room temperature under pressure). Castable resins may be used, particularly when edge retention is unimportant.

Grinding

After mounting, the specimen is abraded (ground) to a condition suitable for polishing. The traditional approach utilizes a series of 120, 240, 320, 400, and 600 grit waterproof silicon carbide abrasive papers. Water is used as the lubricant and to remove abrasion debris from the paper. Many metallographers use a second 600-grit grinding operation without water (i.e., dry) to maximize graphite retention.

If grinding is performed manually on rotating wheels, the specimen is held against the paper, being careful not to rock the specimen. It is moved from edge to center as the wheel rotates (generally at 150 to 300 rpm). After grinding with each paper, the specimen is reoriented 45 to 90° from the prior direction and ground with the next paper. When automatic devices are used, a multidirectional scratch pattern is produced, and thus specimen reorientation is not required. Automatic devices provide best flatness and graphite retention.

Abrasion on the final paper is an important stage in the preparation procedure, because it is here that the graphite phase may be damaged. For most gray irons containing fine graphite structures, white irons, and alloy irons, careful abrasion on 600 grit paper is normally sufficient before polishing. A generally recommended 600 grit grinding procedure is first stage with water lubrication and the second stage dry.

In the article "Metallographic Practices Generally Applicable to All Metals," Fig. 24(a) shows a coarse-flake gray iron that has been abraded on a poor-quality abrasive paper. The graphite flakes have been torn out and the cavities enlarged. This effect can also be due to other factors, such as grinding with worn or loaded papers, or grinding in the same direction with each paper grade. Figure 24(b), which is essentially the same field as Fig. 24(a), shows the specimen after it has undergone correct abrasion. The graphite flakes are well preserved, and the matrix is uniformly scratched. In this article, Fig. 4 and 5 show (at high magnification) a single graphite nodule in a ductile cast iron in the incorrectly and correctly abraded states.

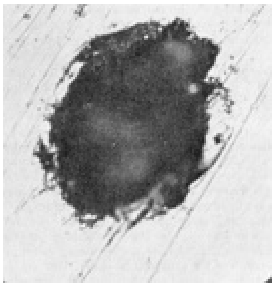


Fig. 4 Nonretained graphite nodule in a ductile iron specimen after incorrect abrasion. The graphite phase has been torn away. Not polished, not etched. 800×

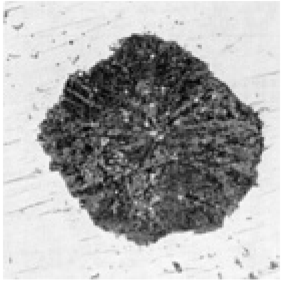


Fig. 5 Same specimen as in Fig. 4 but after correct abrasion, which yields a fully retained nodule. Note that the graphite spherulite has been well preserved. As polished, not etched. 800×

Polishing

For cast iron, polishing with diamond abrasives has been found to be most satisfactory. Polishing in two stages is recommended. Coarse polishing frequently is performed with 6 μm diamond, and fine polishing with 1 μm diamond. In some instances, finer diamond pastes can be employed. The paste is supplied in syringe applicators from which it is squeezed in the form of a thin ribbon. The action of diamond-impregnated carrier pastes produces rapid polishing with minimum deformation. Diamond slurries are also utilized.

Polishing is an important phase of the preparation sequence, because properly ground specimens can be damaged by poor polishing technique. Use of inadequate lubricant, a worn cloth, an inadequately charged cloth, or excessive pressure or wheel speed can degrade graphite retention, enlarge the apparent size of the graphite, produce scratched surfaces, and reduce interface sharpness. For gray irons, in order to polish the graphite and remove distorted and smeared metal, alternate polishing and etching is sometimes practiced.

The type of polishing cloth used with the diamond abrasive has a significant effect on retention of graphite. Polishing cloths with a high nap or pile are extremely effective in removing scratches from previous operations, but they have an adverse effect on retention of graphite. Napless or short-pile cloths are more suitable for retaining graphite but suffer from the limitation that they are less efficient in removing abrasion scratches. With two-stage polishing, a napless cloth is used for the rough polishing stage, while a low-nap or napless cloth is used for the final diamond polishing stage.

After polishing, the specimen surface is cleaned by swabbing with a soapy water solution followed by rinsing with alcohol from a squeeze-type wash bottle. If cavities are present, ultrasonic cleaning may be needed. The specimen is dried by flooding it with high-purity alcohol and then holding it under the hot air blast from a specimen dryer.

Etching

If an assessment of graphite shape, size, and distribution is required, this is best done when the specimen is in the as-polished (not etched) condition. Examination for porosity or the presence of nonmetallic inclusions is also more easily achieved when the specimen is polished but not etched. However, observation of other important structural details can be made only after the specimen has been suitably etched. This step is normally done by holding the specimen with a pair of tongs and immersing it, with intermittent agitation, in the desired reagent for a suitable period of time.

The production and interpretation of correctly etched cast iron structures is often dependent on practice and experience, because consideration usually has to be given to both the characteristics of the reagents used and the nature of the investigation. Table 3 gives some of the more common etching reagents employed for cast iron, together with techniques for use and their principal applications. Most cast irons can be satisfactorily etched with either 4% picral or 2% nital.

Table 3 Etchants for microscopic examination of cast irons

Etchant	Composition	Etching technique	Applications
Picral	4% picric acid, 96% ethanol	Dip etch for 2-10 s	General-purpose etching of all pearlitic gray, malleable, and ductile cast irons. Best etchant for pearlite. Etches some austenitic cast irons, Ni-hard, and acicular irons.
Nital, 5%	5% nitric acid, 95% ethanol	(1) Dip etch for 2-10 s (2) Electrolytic etch[(a)]	(1) General-purpose etching of all ferritic gray, malleable, and ductile cast irons. Etches grain boundaries. Etches some austenitic irons and containing martensite. (2) High-chromium irons
Nital, 2%	2% nitric acid, 98% ethanol	Dip etch for 2-10 s	Observation of ferritic grain boundaries at high magnification
Ferric chloride	10 g ferric chloride, 100 mL water	Dip etch for 3-20 s	Austenitic cast irons
Mixed acid in glycerol	10 mL HNO_3, 20 mL HF, 40 mL glycerol	Dip etch for 10-40 s	High-silicon irons (14 to 16% Si)
Vilella's reagent	1 vol HNO_3, 2 vol HCl, 3 vol glycerol	Dip etch for up to 20 s	High-chromium irons
Potassium ferricyanide	10% alkaline aqueous solution of potassium ferricyanide	Dip etch for 5-30 s, in etchant at 50 °C (122 °F)	High-chromium irons
Murakami's reagent	10 g KOH, 10 g $K_3Fe(CN)_6$	(1) Dip etch for 2-3 min (2) Dip etch for 10-30 s	(1) 30% chromium irons. (2) High-phosphorus irons, to distinguish between iron phosphide and iron carbide
Alkaline sodium picrate	2 g picric acid, 25 g NaOH, 100 mL water; warm to dissolve	(1) Dip etch for 10 s to 2 min at boiling point (2) Electrolytic etch[(b)]	(1) Blackens cementite. (2) Blackens cementite

(a)	Specimen is anode; platinum cathode. Current density, 0.13 to 0.31 A/cm^2 (0.5 to 2.0 A/in^2) for up to 2 min.
(b)	Specimen is anode; stainless steel cathode. Current density, 0.13 to 0.31 A/cm^2 (0.5 to 2.0 A/in.^{2}) for up to 2 min in cold solution.

Picral is the best general-purpose etchant for all predominantly pearlitic gray, malleable, and ductile cast irons. It gives a clean, uniform etch to both coarse and fine pearlitic structures. Pearlite should be etched until it is medium-to-light brown in color, so that graphite present in the structure can be clearly seen. Picral does not damage graphite but gives an added sharpness to the outline of the flakes or nodules.

Macroexamination

Macroetching of cast iron is used to reveal such features as chill formation and segregation. Table 4 gives the more commonly used macroetchants for cast iron. Usually, picral, nital, and ammonium persulfate are the most suitable reagents because they do not cause extensive staining. The specimens should be immersed in the solution and swabbed with cotton. After removal from the etchant, they are flooded with water, rinsed with alcohol, and dried with hot air.

Table 4 Etchants for macroscopic examination of cast irons

Etchant	Composition	Etching technique	Application
Stead's reagent	10 g cupric chloride, 40 g magnesium chloride, 20 mL hydrochloric acid, 1000 mL ethanol[(a)]	Immersion for up to 3 h	Used to reveal the eutectic cell number in gray cast irons
Rapid cell-etching reagent	10 g cupric chloride, 50 mL water, 100 mL hydrochloric acid	Dip etch for about 60 s	As above, but results are less distinct
Ammonium persulfate	10 g ammonium persulfate, 100 mL water, few drops H_2SO_4 (conc)[(b)]	Immersion and swabbing	Reveals carbide and phosphide distribution
Nital	5 or 10% nitric acid, 95 or 90% ethanol	Dip etch for up to 3 min	Used to reveal macrostructure in white irons
4% picral	4% picral acid, 96% ethanol	Dip etch for up to 3 min	Used to reveal macrostructure in white irons

(a) Dissolve cupric chloride in a minimum quantity of hot water (10-15 mL); add magnesium chloride and dissolve; add ethanol, then hydrochloric acid.

(b) Add H_2SO_4 just before use.

Eutectic cells in gray irons are generally revealed by etching with Stead's reagent. The reagent selectively darkens low-phosphorus regions in the iron, leaving high-phosphorus regions (normally segregated at cell boundaries) unattacked and light. The specimens can be etched by immersion in a stock solution for periods up to 3 h. The time of immersion is found by trial, but, in general, irons containing coarse cell structures take longer than irons containing fine cell structures.

Technique for Tool Materials

METALLOGRAPHIC TECHNIQUES for tool steels, cast cobalt alloy tool materials, cemented carbides, and ceramic tool materials are described in this section because of the similar nature of their use and metallographic procedures, despite the fact that only tool steels are iron-base materials.

Tool Steels

The procedures used for specimen preparation and macroscopic and microscopic examination of tool steels are essentially the same as those used for carbon and alloy steels.

Macroetching. A solution containing one part hydrochloric acid and one part water at 71 to 82 °C (160 to 180 °F) is the etchant most often used for revealing segregation, porosity, cracks, inclusions, and flow lines. This etchant also can be used for revealing hardness penetration and soft spots. A solution of nitric acid (2 to 10% in water or ethanol) is often favored for showing the depth of the hardened zone, carburized case depth, or decarburized depth; it is used to a lesser extent for revealing defects.

Preparation of Specimens for Microscopy. The test piece is obtained from the larger mass by breaking, hacksawing, or abrasive cutoff. Hacksawing is limited to annealed specimens. Use of abrasive cutoff wheels for sectioning tool steels requires extreme care to prevent overheating. In sectioning of pieces that have been hardened but not tempered, it is inadvisable to permit them to exceed a temperature of about 66 °C (150 °F). Steels that contain large amounts of massive carbide particles, such as D2 and T15, are very difficult to cut, even when in the annealed condition, and require ultimate care when abrasive cutoff is used. A soft grade of cutoff wheel, a copious supply of coolant, and slow cutting speed are mandatory. The cut surface must always be inspected for evidence of burning.

Mounting techniques are the same for tool steels as for other steels. Phenolics or epoxies are most often used as the mounting materials. Phenolics are a satisfactory material except for mounting hardened but untempered specimens, which should not be subjected to the required thermosetting temperatures. A castable mounting compound (e.g., an epoxy) that hardens at room temperature, or at no more than about 66 °C (150 °F), is preferred for most hardened but untempered tool steels.

Grinding and polishing techniques are basically the same for tool steel specimens as for specimens of carbon and alloy steels. It is important to keep polishing times as short as possible, especially for steels such as D2 and T15. Excessive polishing produces a relief effect due to the carbide particles and may pull out or drag inclusions. Use of napless or low-nap cloths help reduce relief problems.

Microetching with Nital. For routine metallographic examination, tool steel specimens are most often etched in 2 to 5% nital (2 to 5 mL of nitric acid added to ethanol or methanol to make 100 mL of etchant). Nital is a general-purpose etchant and can be used on all tool steels in nearly all conditions: annealed, quenched, and quenched-and-tempered. Nital, however, is relatively poor for spheroidize-annealed tool steels. Picral, perhaps aided by a small addition of HCl (0.5 to 4%), is far better for revealing the spheroidized carbides. Vilella's reagent is also widely used to study tool steel structures.

Because of the many variables affecting etching time, it is impractical to prescribe specific etching times. Common practice is to immerse the specimen in the etchant with the polished side up, agitate it gently, and observe it carefully. The surface of the specimen first changes from a polished appearance to light brown. If etching proceeds too far, the specimen turns dark gray. Overetching causes a loss of detail in the matrix and shows the carbides heavily in relief. Overetching may result in removal of the carbide particles. Alternate etching and microscopic observation may be required to obtain the ideal etch for the magnification to be used. Etching of quenched but untempered highly alloyed tool steels for grain-size observation may require up to 4 or 5 min in 2% nital.

Microetching with picral, a 4% solution of picric acid in ethanol, is applicable for most grades of tool steel, particularly in the annealed condition. Various carbide structures are shown better if the specimen is etched with picral rather than with nital. Techniques for etching with picral are essentially the same as those for etching with nital. Picral is not as effective as nital for the study of martensitic structures. The addition of HCl or the use of Vilella's reagent overcomes this problem.

Special-purpose etchants are occasionally used for etching of tool steels. They are used for greater distinction of specific microconstituents (Table 5), particularly carbides.

Table 5 Special-purpose etchants for tool steels

Feature	Etchant	Comments
Cementite	2 g picric acid, 25 g NaOH, 100 mL water	Immerse in boiling solution or use electrolytically (6V dc, 20 °C, 30-120 s). Will not darken cementite if it contains substantial Cr.
M_6C, Mo_2C	4 g $KMnO_4$, 4 g NaOH, 100 mL water	Use by immersion.
MC, M_7C_3	1 g CrO_3, 100 mL water	Electrolytic at 2-3 V dc, 30 s

Cast Cobalt Alloy Tool Materials

The cast cobalt alloy tool materials are a unique family of proprietary alloys that are hard in the as-cast condition and are used without further heat treatment. Most of them contain 38 to 50% Co, 25 to 32% Cr, 4 to 25% W, and 1 to 4% C. Some of these alloys contain up to 4% V, and others have up to about 5.5% Nb and 3.5% Fe.

Microstructure. The most noticeable constituent is large carbides that appear in elongated or acicular form and have been identified as chromium carbide, Cr_7C_3, in which some of the chromium may be replaced by cobalt or tungsten. M_6C

and $M_{23}C_6$ carbides have been identified in some alloys. The matrix usually consists of various binary and ternary eutectics containing all constituents of the alloy.

Specimen Preparation. Sectioning is done using abrasive cutoff wheels. The greatest care must be used to prevent damage from overheating. Use a very softly bonded wheel with copious water cooling. If phenolics are used as the mounting material, the heat involved in curing is not sufficient to alter the structure of the alloys. Grinding and polishing are done by the same procedures as those used for grinding and polishing carbon steels, alloy steels, and tool steels.

Etching procedures and etchants for cast cobalt alloy tool materials differ among various laboratories. The two procedures that follow are commonly used.

The first commonly used procedure begins by activating the surface of the polished specimen with a short (about 2 s) electrolytic etch in 2% chromic acid, then immersing the specimen for 10 s in an alkaline permanganate solution. The alkaline permanganate solution is prepared immediately before use by mixing equal parts of a saturated solution of potassium permanganate and an 8% solution of sodium hydroxide. It should be discarded immediately after use. After etching, wash the specimen in running water and then in ethanol or methanol, and dry it in an air blast. The etched specimen must not be rubbed.

The other method starts by etching the specimen for about a minute (the exact time is determined by trial and error) in a solution of six parts of concentrated hydrochloric acid and one part of 30% hydrogen peroxide. Etching must be done under a hood.

Cemented Carbides

Both low and high magnifications are used for examining microstructures of cemented carbides.

Examination at Low Magnifications. Macroscopic examination of cemented carbides is usually practiced with a low-power microscope at 20 or 30 diameters for detecting pits, pressing flaws, contamination, segregation, free carbon, and carbon deficiency (eta phase). Free carbon is characterized on an as-sintered surface or a fracture surface by clustered dark spots. Often, a specimen with excessive free carbon has an as-sintered surface that feels slippery to the touch. Carbon deficiency is manifested by the appearance of shiny stringers, dots, and clusters that turn dark when etched with Murakami's reagent. Because defects, such as pits and pressing flaws, lower the strength of the material, fracture will initiate in them and propagate through them. For this reason, they are easy to identify on a fracture surface.

Preparation of Specimens for Microscopy. The specimen is extracted from a larger mass by breaking or by abrasive-wheel cutting. Cutting with a precision diamond saw is widely practiced because it produces little damage and yields a surface requiring a minimum of grinding. Diamond is the most effective abrasive for sectioning these very hard materials. Because cemented carbides are difficult to polish (due to the structure and hardness), it is recommended that the size of the specimen be kept as small as possible. Specimens having a face area no larger than 160 mm^2 ($\frac{1}{4}$ $in.^2$) are preferred.

The mounting materials and techniques that are applicable to steels are applicable also to cemented carbides. All compression mounting compounds may be used.

Because cemented carbides are very hard, hand grinding and polishing is quite tedious, and use of automatic devices is recommended. If the specimen has been cut with a precision diamond saw, a high-quality surface is obtained that requires a minimum of grinding. SiC papers are rather inefficient for grinding cemented carbide specimens. Metal- or resin-bonded diamond disks are preferred. These disks are available with a wide range of nominal diamond sizes, depending upon the type and source, but generally are in the range of 165 to 15 μm (may be available with coarser or finer diamond sizes). If the surface to be polished has been sectioned by fracturing, the coarsest diamond size should be used first. If the surface was cut with a precision diamond saw, grinding can commence with the 30 μm diamond disk. Grinding is done with relatively high pressure, copious water cooling, and a speed of 100 to 300 rpm.

Polishing generally is conducted in several stages using diamond paste on napless or low-nap cloths. Nylon is frequently used. Diamond charging is heavier than for polishing of steels. The cloth should be moistened with extender lubricant and not be permitted to dry out. Polishing with 6 and 1 μm diamond paste is recommended. Again, the pressure is somewhat higher than that used for steels, and automatic devices are definitely preferred. For most work, final polishing with 1 μm diamond is adequate. A short 30 s final hand polish with colloidal silica may be desirable for best results. This step is performed using a short- or medium-nap synthetic cloth attached to a glass plate (i.e., stationary) using a figure-eight motion. This step will reveal the interfaces between the cobalt binder and the carbides with a minimum of relief. Alternatively, a vibratory polisher may be used.

Etching. The most commonly used etchant for cemented carbides is aqueous alkaline potassium ferricyanide, known as Murakami's reagent (10 g potassium ferricyanide, 10 g potassium hydroxide, or 7 g sodium hydroxide), and 100 mL water. A short etch (2 to 10 s) colors only eta phase. Longer etching times attack the eta phase but reveal the phase boundaries. Etching is performed at room temperature.

To preferentially darken the cobalt binder phase, etch for 1 to 5 min at room temperature in hydrochloric acid saturated with ferric chloride (Chaporova's reagent). The cobalt binder phase also may be revealed preferentially by heat tinting the polished specimen (unmounted) at 315 °C (600 °F) for 5 min in a laboratory furnace. This practice colors the cobalt rust brown. Higher temperatures will color the carbide grains. Considerable use has also been made of the Pepperhoff vacuum-deposition interference-film technique (Ref 1).

Apparent porosity is a "catch-all" term that refers to all microstructural features observed at a magnification of 200 diameters on properly prepared, unetched surfaces of cemented carbides. The apparent porosity rating is made by comparing the observed field with a porosity chart, such as that provided by ASTM B 276. Free carbon can be confirmed as C-type apparent porosity at 200 diameters. Segregation and contamination can be observed also.

Microstructure. Examination of the microconstituents of cemented carbides is best done at magnifications of 1000 to 1500 diameters after etching by immersion in Murakami's reagent at room temperature. Tungsten carbide is revealed as gray angular crystals; cobalt, unattacked by the etch, appears as a white or light-cream matrix. If tantalum carbide, titanium carbide, or solid-solution phases are present, they will appear brownish or gold in color, and will stand above the polished surface when etched. The different phases are distinguished by slight differences in color.

Because each producer manufactures cemented carbide materials for performance under given conditions according to its own specifications as to microstructure, considerable differences will be observed in the microstructures of materials from different producers. Thus, the value of a microscopic examination, beyond evaluation of apparent porosity and examination for extraneous phases, will depend on the correlation developed between a specific microstructure and performance.

To estimate the grain size of cemented carbide materials, the microstructure is compared with a set of standard charts or micrographs. A visual comparison procedure for evaluating the apparent grain size of cemented tungsten carbide materials is described in ASTM B 390. Alternatively, the size of the WC grains can be measured manually or by image analysis.

Reference cited in this section

1. W. Peter, E. Kohlhaas, and O. Jung, Revealing of Hard Metal Structures by Interference Vapor-Deposition, *Prakt Metallographie,* Vol 4, June 1967, p 284-290

Ceramic Tool Materials

The steps used in preparing and polishing specimens from ceramic (oxide-base) tool materials for microscopic examination are essentially the same as those for preparing specimens from cemented carbides. Because of the absence of a ductile matrix phase in most ceramic tool materials, extreme care is required during polishing to prevent pullout of hard, brittle particles. Specimens to be etched are not mounted in plastic, because of the high temperatures that may be required for etching.

The polished, unetched specimen is viewed at magnifications of 100 to 1000 diameters to determine porosity, flaws, and segregation. Because complete freedom from pullouts may be difficult to attain, density measurements are used as the primary means of determining porosity, with microscopic examination employed for confirmation.

If etching is desired, the polished, unmounted specimen is immersed in 85% H_3PO_4 at 180 to 250 °C (360 to 480 °F) for 8 to 10 min. The etchant preferentially attacks second phases and grain boundaries, and this must be taken into account in an interpretation of the etched microstructure.

Technique for Ferrous Powder Metallurgy Alloys

POWDER METALLURGY PARTS may not be compacted to full density, with the result that there are invariably some pores, the number and size of which will vary with density. The major difference between parts made from metal powders and those made from wrought metal is in the amount of porosity (voids). The presence of pores is likely to cause difficulty in the preparation of metallographic specimens. First, there is the possibility that grinding debris, abrasive or particles of other metals will become embedded in the pores during cutting, grinding, and polishing. Also, moisture may become entrapped in the pores and may bleed out during etching, resulting in staining. Another possibility is the entrapment of etchant, which may bleed out and stain the surface.

Specimen Selection and Sectioning

Selection of representative specimens of powder metallurgy alloys requires careful consideration, primarily because porosity is seldom uniform. Density (and therefore porosity) may vary from surface to center of a relatively thick part, thus necessitating examination of the entire cross section. Also, when a powder metallurgy part is subjected to a furnace atmosphere, as in sintering or heat treatment, microstructural characteristics may be different within a given cross section.

Washing

Following sectioning, specimens should be washed to remove foreign material that may have infiltrated the pores. Two devices used for removing contaminants from pores are an extractor-condenser and an ultrasonic cleaner.

Extractor-Condenser. The use of an extractor-condenser is the more efficient and the less expensive of the two methods of washing. The extractor-condenser consists of a flask, a siphon cup, and a condensing-coil unit that fits on the top of the flask (Fig. 6). A solvent, such as acetone, is placed in the flask, and the specimens to be washed are placed in the siphon cup. A cold-water line is connected to the condensing coil. The flask is heated to the boiling temperature of the solvent. The solvent evaporates and, when the vapor comes in contact with the cold condensing coil, it condenses and drips into the siphon cup. When the siphon cup becomes filled to a predetermined level, it empties, returning the solvent to the flask. Recycling allows a continuous flow of clear solvent over the specimen.

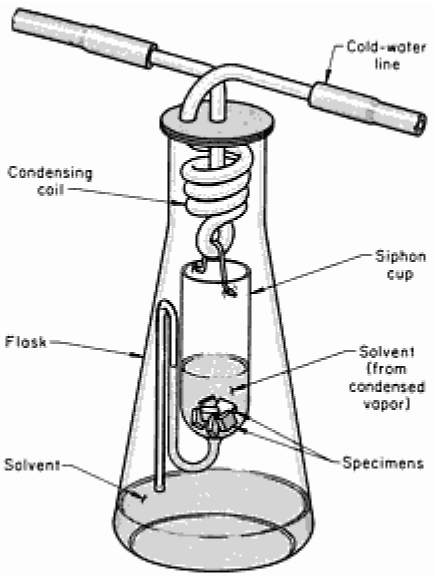


Fig. 6 Extractor-condenser used to wash P/M specimens to remove contaminants from pores

Ultrasonic Cleaning. The ultrasonic cleaner used for washing powder metallurgy specimens consists of a power supply and a small tank, which holds a solvent bath. Numerous solvents may be used, for example, a warm aqueous solution containing a detergent, alcohol, or acetone. The specimens must be fully dried after cleaning, which may require baking in an oven at 50 to 65 °C (120 to 150 °F).

Impregnation

After the specimen has been washed, some means of preventing abrasives, water, and etchant from entering the pores should be provided. For specimens that are to be ground and polished without mounting or that are to be mounted using heat and pressure (as required for a phenolic), wax impregnation is recommended. Specimens are impregnated by soaking them in a molten synthetic wax at 175 °C (350 °F) for 2 to 4 h. After cooling and removal of the surface wax, the specimens are ready for mounting or for grinding and polishing without mounting.

Vacuum impregnation using a very low viscosity epoxy is also commonly performed. Impregnation is done after grinding. When the epoxy is dry, the surface is lightly reground with the finest grit used before polishing. Figure 7 shows views of a commercially available system for vacuum impregnating specimens in epoxy.

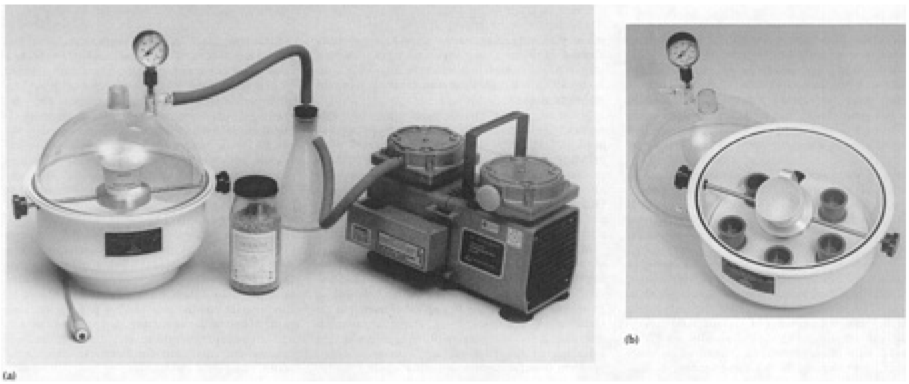


Fig. 7 Vacuum impregnation equipment. (a) Complete system. (b) A view of the inside of the chamber prior to use

These practices will fill only those pores connected to the surface. After grinding and polishing, new pores may be opened at the surface that were not previously filled because they were not connected to the surface. A second wax treatment or epoxy infiltration step may be needed before the final preparation step.

Mounting and Grinding

Mounting of specimens is always preferable, and it is required for very small specimens and for edge preservation. The materials and techniques used for mounting powder metallurgy specimens are similar to those for mounting specimens of other metals.

Grinding. Procedures for grinding powder metallurgy specimens are generally the same as for specimens of other metals.

Polishing. Rough polishing is best accomplished on a napless cloth, such as nylon, charged with abrasive, usually diamond, with sizes from 9 to 3 μm. Automated polishing devices are helpful when preparing porous metals. Excessive relief introduced during polishing will enlarge the porosity and give a false impression of its size and amount. Fine polishing of powder metallurgy alloys is generally the same as for other metals employing fine diamond (e.g., 1 μm) or alumina (0.3 and/or 0.05 μm). Colloidal silica and acidic alumina solutions are also popular for final polishing, particularly with a vibratory polisher.

Etching. Ferrous powder metallurgy alloys are almost always etched by immersion in 2% nital, although picral is sometimes used and is preferred by some metallographers for revealing certain structures. Staining problems usually are easier to control after etching with nital than with picral.

Technique for Wrought Stainless Steels

WROUGHT STAINLESS STEELS are complex alloys containing a minimum of 11% Cr plus other elements to produce ferritic, martensitic, austenitic, duplex, or precipitation-hardenable grades. Procedures used to prepare wrought stainless steels for macroscopic and microscopic examination are similar to those used for carbon and alloy steels and for tool steels. However, certain types require careful attention to prevent artifacts. Because the austenitic grades work-harden readily, cutting and grinding must be carefully executed to minimize deformation. The high-hardness martensitic grades that contain substantial undissolved chromium carbide are difficult to polish while fully retaining the carbides. The most difficult of such grades to prepare is AISI 440C, particularly in the annealed or annealed-and-quenched conditions. For the most part, preparation of stainless steels is reasonably simple if the basic rules for metallographic preparation are followed. However, unlike carbon, alloy, and tool steels, etching techniques are more difficult due to the high corrosion resistance of stainless steels and the various second phases that may be encountered.

Macroexamination

The procedures used to select and prepare stainless steel disks for macroetching are identical to those used for carbon, alloy, and tool steels. Because these grades are more difficult to etch, however, all surfaces to be etched must be smooth ground or polished. Saw-cut surfaces will yield little useful information if they are macroetched.

Macroetchants for stainless steels are listed in Table 6. Heated macroetchants are used with stainless steels in the same manner as carbon, alloy, or tool steels. Etchant compositions are often more complex and more aggressive. In the study of weld macrostructures, it is quite common to polish the section and use one of the general-purpose microetchants.

Table 6 Macroetchants for wrought stainless steels

Etchant		Comments
1	50 mL HCl, 10 g $CuSO_4$ (copper sulfate), 50 mL H_2O[(a)]	Marble's reagent. General-purpose macrotech; can be heated
2	50 mL HCl, 50 mL H_2O, 20 mL 30% H_2O_2	Mix HCl and H_2O, heat to 70-75 °C (160-170 °F). Immerse specimen and add H_2O_2 in steps when foaming stops; do not mix
3	(a) 15 g $(NH_4)_2S_2O_8$ (ammonium persul fate) and 75 mL H_2O (b) 250 g $FeCl_3$ and 100 mL H_2O (c) 30 mL HNO_3	Lepito's No. 1 etch. Combine (a) and (b), then add (c); immerse specimen at room temperature; use fresh
4	1 part HCl and 1 part H_2O	Standard hot-etch. Use at 70-80 °C (160-180 °F), 15-45 min; desmut by dipping in warm 20% aqueous HNO_3 solution to produce a bright surface
5	10-40 mL HNO_3, 3-10 mL 48% HF, 25-50 mL H_2O	Use at 70-80 °C (160-180 °F); immerse until the desired degree of contrast is obtained
6	50 mL HCl and 25 mL saturated $CuSO_4$ in H_2O	Use at 75 °C (170 °F); immerse until the desired degree of contrast is obtained

(a) When water is specified, use distilled water.

Microexamination

Sectioning and mounting techniques for stainless steels are identical to those for carbon, alloy, or tool steels.

Grinding is performed using 120, 240, 320, 400, then 600 grit water-cooled SiC papers. Care must be taken, particularly when grinding austentic grades, to remove the cold work from cutting and from each grinding step. In general, speeds of approximately 300 rpm and moderate, firm pressure are used. Grinding times are 1 to 2 min per step. If grinding is carried out by hand, the specimen should be rotated 45 to 90° between each step. Automatic grinding devices produce omnidirectional grinding patterns.

Polishing. After grinding, specimens are usually rough polished using 6 or 3 μm diamond as a paste, spray, or slurry on napless, low-nap, or medium-nap cloths. Edge flatness and inclusion retention are usually improved by using napless cloths, although scratch removal may not be as complete as with medium-nap cloths. A lubricant extender compatible with the diamond abrasive should be used to moisten the cloth and reduce drag. A wheel speed of approximately 150 rpm is usually adequate. Pressure should be moderate and firm; specimen rocking should be avoided if polishing is carried out by hand.

To produce high-quality, scratch-free surfaces suitable for photomicroscopy, specimens should be final polished using one or more fine abrasives. The most commonly used final abrasives are 0.3 μm α-alumina (Al_2O_3) or 0.05 μm γ-Al_2O_3. Medium-nap cloths are usually used. Polishing with these abrasives, mixed as a water slurry, is performed in the same manner as diamond polishing. Specimens should be carefully cleaned between each rough and final polishing step to avoid contamination at the next step. Colloidal silica is a highly suitable final abrasive for stainless steels.

Stainless steels, particularly the austentic grades, are often polished electrolytically. In most cases, electropolishing is performed after grinding to a 600 grit SiC finish. Table 7 lists recommended procedures. Electropolishing usually produces high-quality, deformation-free surfaces; however, inclusion attack is encountered, and second phases may be attacked preferentially.

Table 7 Electropolishing procedures for wrought stainless steels

Electrolyte composition		Comments
1	50 mL $HClO_4$ (per chloric acid), 750 mL ethanol, 140 mL H_2O(a)	Add $HClO_4$ last, with care. Use at 8-20 V dc, 0.3-1.3 A/cm^2 (1.9-8.4 A/$in.^2$), 20 °C (70 °F), 20-60 s. Rinse immediately after polishing
2	78 mL $HClO_4$, 90 mL H_2O, 730 mL ethanol, 100 mL butyl cellusolve	Add $HClO_4$ last, with care. Use at 0.5-1.5 A/cm^2 (3.2-9.7 A/$in.^2$), 20 °C (70 °F) max
3	62 mL $HClO_4$, 700 mL ethanol, 100 mL butyl cellusolve, 137 mL H_2O	Add $HClO_4$ last, with care. Use at 1.2 A/cm^2 (7.7 A/$in.^2$), 20 °C (70 °F), 20-25 s
4	25 g CrO_3, 133 mL acetic acid, 7 mL H_2O	Use 20 V dc, 0.09-0.22 A/cm^2 (0.58-1.4 A/$in.^2$), 17-19 °C (63-66 °F), 6 min. Dissolve CrO_3 in solution heated to 60-70 °C (140-160 °F)
5	37 mL H_3PO_4, 56 mL glycerol, 7 mL H_2O	Use at 0.78 A/cm^2 (5.0 A/$in.^2$), 100-120 °C (212-250 °F), 5-10 min
6	6 mL $HClO_4$ and 94 mL ethanol	Use at 35-40 V dc, 24 °C (75 °F), 15-60 s

(a) When water is specified, use distilled water.

Etching. For inclusion examination, etching is not required, although it is necessary for examining the microstructure. Although the stainless steels are reasonably easy to polish, etching is generally a more difficult step. The corrosion resistance of stainless steels and the potential microstructural complexity of these alloys makes selection of the best etchant a more difficult problem than for carbon and alloy steels.

Stainless steel etchant ingredients are dissolved in water, methanol or ethanol, glycerol, or a mixture of these solvents. Reagents with alcohol or glycerol as the solvent provide better wetting of the surface than water-based reagents and generally provide more uniform etching. Because alcohol reduces dissociation, alcohol-base reagents can be made more concentrated without becoming too powerful for controlled etching. Stainless steel surfaces passivate; therefore, reducing conditions are preferred to oxidizing conditions that promote passivity. Consequently, stainless steel etchants often contain hydrochloric (HCl), sulfuric (H_2SO_4), or hydrofluoric (HF) acid, although nitric acid (HNO_3) may be used alone or mixed with HCl to produce aqua regia or a modified aqua regia. Swabbing, instead of immersion, may be desired to obtain more uniform etch results. Electrolytic etching is also very popular because it produces uniform etching, is easier to control, and gives reproducible results. Table 8 lists numerous etchants used for microexamination of stainless steels.

Table 8 Microetchants for wrought stainless steel

Etchant		Comments
1	1 g picric acid, 5 mL HCl, 100 mL ethanol	Vielella's reagent. Use at room temperature to 1 min. Outlines second-phase particles (carbides, σ phase, δ-ferrite), etches martensite
2	1.5 g $CuCl_2$ (cupric chloride), 33 mL HCl, 33 mL H_2O(a)	Kalling's No. 1 reagent for martensitic stainless steels. Use at room temperature. Martensite dark, ferrite colored, austenite not attacked
3	5 g $CuCl_2$, 100 mL HCl, 100 mL ethanol	Kalling's No. 2 reagent. Use at room temperature. Ferrite attacked rapidly, austenite slightly attacked, carbides not attacked
4	5 g $CuCl_2$, 40 mL HCl, 30 mL H_2O, 25 mL ethanol	Fry's reagent. For martensitic and precipitation-hardenable grades. Use at room temperature.
5	4 g $CuSO_4$, 20 mL HCl, 20 mL	Marble's reagent. Used primarily with austenitic grades. Use at room temperature to 10 s. Attacks

	H_2O	σ phase
6	3 parts glycerol, 2-5 parts HCl, 1 part HNO_3	Glyceregia. Popular etch for all stainless grades. Higher HCl content reduces pitting tendency. Use fresh, never stored. Discard when reagent is orange colored. Use with care under a hood. Add HNO_3 last. Immerse or swab few seconds to a minute. Attacks σ phase, outlines carbides. Substitution of water for glycerol increases attack rate.
7	45 mL HCl, 15 mL HNO_3, 20 mL methanol	Methanolic aqua regia. Used with austenitic grades to reveal grain structure, outline ferrite and σ phase
8	15 mL HCl, 5 mL HNO_3, 100 mL H_2O	Dilute aqua regia for austenitic grades. Uniform etching of austenite, outlines carbides, σ phase, and ferrite (sometimes attacked)
9	4 g $KMnO_4$ (potassium permanganate), 4 g NaOH, 100 mL H_2O	Groesbeck's reagent. Use at 60-90 °C (140-195 °F) to 10 min. Colors carbides dark, σ phase gray, ferrite and austenitic not affected
10	30 g $KMnO_4$, 30 g NaOH, 100 mL H_2O	Modified Groesbeck's reagent. Use at 90-100 °C (195-212 °F) for 20 s to 10 min to color ferrite dark in duplex alloys. Austenite not affected
11	10 g $K_3Fe(CN)_6$, 10 g KOH or 7 g NaOH, 100 mL H_2O	Murakami's reagent. Use at room temperature to 60 s to reveal carbides; σ phase faintly revealed by etching to 3 min. Use at 80 °C (176 °F) to boiling to 60 min to darken carbides. Sigma may be colored blue, ferrite yellow to yellow-brown, austenite not attacked. Use under a hood.
12	30 g KOH, 30 g $K_3Fe(CN)_6$, 100 mL H_2O	Modified Murakami's reagent. Use at 95 °C (203 °F) for 5 s. Colors σ phase reddish brown, ferrite dark gray, austenite unattacked, carbide black. Use under a hood.
13	10 g oxalic acid and 100 mL H_2O	Popular electrolytic etch, 6 V dc, 25 mm spacing. 15-30 s reveals carbides; grain boundaries revealed after 45-60 s; σ phase outlined after 6 s. Lower voltages (1-3 V dc) can be used. Dissolves carbides. Sigma strongly attacked, austenite moderately attacked, ferrite not attacked
14	10 g NaCN (sodium cyanide) and 100 mL H_2O	Electrolytic etch at 6 V dc, 25 mm spacing, 5 min, platinum cathode. Sigma darkened, carbides light, ferrite outlined, austenite not attacked. Good for revealing carbides. Use with care under a hood.
15	10 mL HCl and 90 mL methanol	Electrolytic etch at 1.5 V dc, 20 °C (70 °F) to attack σ phase. Use at 6 V dc for 3-5 s to reveal structure.
16	60 mL HNO_3 and 40 mL H_2O	Electrolytic etch to reveal austenite grain boundaries (but not twins) in austenitic grades. With stainless steel cathode, use at 1.1 V dc, 0.075-0.14 A/cm^2 (0.48-0.90 A/in.^{2}), 120 s. With platinum cathode, use at 0.4 V dc, 0.055-0.066 A/cm^2 (0.35-0.43 A/in^2), 45 s. Will reveal prior-austenite grain boundaries in solution-treated (but not aged) martensitic precipitation-hardenable alloys
17	50 g NaOH and 100 mL H_2O	Electrolytic etch at 2-6 V dc, 5-10 s to reveal σ phase in austenitic grades.
18	56 g KOH and 100 mL H_2O	Electrolytic etch at 1.5-3 V dc for 3 s to reveal σ phase (red-brown) and ferrite (bluish). Chi colored same as sigma
19	20 g NaOH and 100 mL H_2O	Electrolytic each at 20 V dc, for 5-20 s to outline and color δ-ferrite tan.
20	NH_4OH (conc)	Electrolytic etch at 1.5-6 V dc for 10-60 s. Very selective. At 1.5 V, carbide completely etched in 40 s; sigma unaffected after 180 s. At 6 V, σ phase etched after 40 s
21	10 g $(NH_4)_2S_2O_8$ and 100 mL H_2O	Use at 6 V for 10 s to color carbide dark brown
22	200 mL HCl and 1000 mL H_2O	Beraha's tint etch for austenitic, duplex, and precipitation-hardenable grades. Add 0.5-1.0 g $K_2S_2O_5$ per 100 mL of solution (if etching is too rapid, use a 10% aqueous HCl solution). Immerse at room temperature (never swab) for 30-120 s until surface is reddish. Austenitic colored, carbides not colored. Longer immersion colors ferrite lightly. If coloration is inadequate, add 24 g $NH_4F{\cdot}HF$ (ammonium bifluoride) to stock reagent at left.
23	20 g picric acid and 100 mL HCl	Etch by immersion. Develops grain boundaries in austenite and δ-ferrite in duplex alloys
24	Saturated aqueous $Ba(OH)_2$ (barium hydroxide)	Attacks carbides well before σ phase in austenitic grades when used at 1.5 V dc, but attacks both equally when used at 3-6 V dc. Has been used to differentiate χ phase and Laves phase (use at 4.3 V dc, platinum cathode, 20 s). Chi is stained mottled-purple, Laves is not colored, ferrite is stained tan
25	50 mL each H_2O, ethanol, methanol, and HCl; plus 1 g $CuCl_2$, 3.5 g $FeCl_3$, 2.5 mL HNO_3	Ralph's reagent. Use by swabbing. Can be stored. General purpose etch for most stainless steels. Does not attack sulfides in free-machining grades

(a) When water is specified, use distilled water.

Technique for Stainless Steel Casting Alloys

STAINLESS STEEL CASTING ALLOYS referred to in this section are widely used to resist corrosion by aqueous solutions at or near room temperature and by hot gases and high-boiling-point liquids at temperatures up to 650 °C (1200 °F). All these alloys, which are identified in the United States by ACI designations, contain more than 11% Cr and up to 30% Ni.

Microstructures of stainless steel casting alloys generally are similar to those of their wrought counterparts, except that the segregation inherent in the casting process is not altered. Hence, the microstructures usually are coarser and more diverse, and porosity or shrinkage cavities may be observed.

Grinding and Polishing. The techniques and equipment used for mounting, grinding, and polishing specimens of stainless steel casting alloys for metallographic examination are essentially the same as those used for wrought stainless steels. Coarse and fine grinding, by the traditional method, require the successive use of increasingly finer abrasive papers. Coarse grinding is generally done on SiC papers with grit sizes of 80, 100, or 120 grit (depending upon the roughness and depth of damage of the cut surface), and it is followed by fine grinding on papers with grit sizes of 240, 320, 400, and 600 grit. Coarse grinding can be avoided if the surface being prepared is properly sectioned using an abrasive cutoff wheel. Rough polishing entails the successive use of rotating disks covered with napless cloth impregnated with diamond abrasive with particle sizes of 9, 6, 3, and 1 μm (two of these steps are sufficient). Rotating wheels covered with medium-nap cloths and slurries of alumina of 0.3 and 0.05 μm particle size are used for fine polishing. Alternatively, colloidal silica or acidic alumina may be used as the final abrasive.

Cast stainless steel specimens may also be prepared using the contemporary preparation procedure described previously. This type of practice is more efficient, and, when napless and low-nap cloths are used, surfaces are produced that accurately reflect the amount of porosity and reveal the structure with proper relief control.

Etching. Among the etchants used to delineate the microstructure of stainless steel casting alloys are those for which compositions are given in the upper part of Table 9. As shown in the lower part of Table 9, the alloys are etched to reveal general microstructure or to emphasize a microconstituent of major interest, such as ferrite or carbide. The presence of ferrite in the CF-type alloys is of practical significance, because small amounts of ferrite improve resistance to hot cracking.

Table 9 Compositions and applications of etchants for stainless steel casting alloys

Etchant No. and name		Composition
1	Oxalic acid (electrolytic, 6 V)	10 g oxalic acid, 100 mL water
2	Vilella's reagent	5 mL HCl, 1 g picric acid, 100 mL ethanol (95%) or methanol (95%)
3	Kalling's reagent number 2	100 mL HCl, 5 g $CuCl_2$, 100 mL ethanol (95%)
4	Murakami's reagent (unheated)	1 to 4 g $K_3Fe(CN)_6$, 10 g KOH (or 7 g NaOH), 100 mL water
5	Murakami's reagent (boiling)	Same composition as etchant 4, above, but heated to boiling temperature for use
6	Chromic acid (electrolytic, 6V)	10 g CrO_3, 100 mL water
7	10*N* potassium hydroxide (electrolytic, 6 V)	560 g KOH diluted with distilled water to a volume of 1000 mL
8	HCl, HNO_3, acetic acid	15 mL HCl, 10 mL HNO_3, 10 mL acetic acid
9	Acid ferric chloride	Saturated solution of $FeCl_3{\cdot}6H_2O$ in HCl (conc); add few drops HNO_3
10	Glycergia	10 mL HNO_3, 20 to 50 mL HCl, 30 mL glycerol
11	Sodium cyanide (electrolytic, 6 V) (use with extreme care)	10 g NaCN, 90 mL water

Alloy	Normal heat treatment	Etchants for revealing:			
		General microstructure	**Ferrite**	**Carbide**	**Sigma phase**
Application of etchants above to examination of specific alloys					
CN-6NM	Hardened and tempered(a)	2	3	4	. . .
CA-15	Hardened and tempered(a)	2 or 9	3	4	. . .
CD-4MCu	Annealed(b)	1, 2, or 6	. . .	. . .	2 then 7
CE-30	As cast	2	3	4	2 then 7; or 11
CF-3	Annealed(c)	7	3	4	2 then 7
CF-3M	Annealed(c)	8	3	4	2 then 7; or 11
CF-8	Annealed(d)	7 or 10	3	4	2 then 7
CF-8C	Annealed(d)	1 or 6	3	4	2 then 7; or 11
CF-8M	Annealed(d)	9	3	4	2 then 7
CF-20	Annealed(d)	1	3	4	. . .
CG-8M	Annealed(d)	1	3	4	5; or 7 then 11
CN-7M	Annealed(e)	1 or 6	. . .	. . .	. . .

(a) Heat to 955 °C (750 °F) min. air cool and temper at 595 °C (1100 °F) min.

(b) Heat to 1120 °C (2050 °F) min, furnace cool to 1040 °C (1900 °F), quench in water or oil.

(c) Heat to 1040 °C (1900 °F) min, rapid cool.

(d) Heat to 1040 °C (1900 °F) min, water quench.

(e) Heat to 1120 °C (2050 °F) min, water quench

Technique for Fe-Cr-Ni Heat-Resistant Casting Alloys

THE ALLOYS DISCUSSED in this section are iron-base and nickel-base heat-resistant casting alloys containing enough chromium to confer oxidation resistance.

Microstructures. Alloy HA and sometimes, depending on specific composition, alloy HB are hardened by the transformation of austenite during quenching. Thus, austenite transformation products, such as bainite and martensite, may appear in their microstructures. Also, depending on specific composition, the HB and HC alloys may have a matrix of ferrite or austenite, or a mixture of ferrite and austenite; the austenite may be unstable and transform, at least partly, on cooling to room temperature.

Except for the nickel-free alloy HA and low-nickel alloys HB and HC, the matrix of the alloys in the series is austenite. Other microconstituents usually observed are ferrite, several types of chromium carbide, sigma phase, inclusions, and oxides. The HD and HE alloys are intended to be partly ferritic; the presence of ferrite results in lower creep resistance and higher ductility at temperatures of 870 to 1150 °C (1600 to 2100 °F) than for the wholly austenitic alloys. Alloys HD and HE are also more susceptible to the development of the undesirable sigma phase if exposed to temperatures in the range of 650 to 870 °C (1200 to 1600 °F). The HF, HH, HI, HK, and HL alloys are borderline; they can be partly ferritic and partly austenitic or wholly austenitic, depending on composition. As usually supplied, the HI and HK alloys seldom show ferrite. The HN, HP, HT, HU, HW, and HX alloys are wholly austenitic; neither ferrite nor sigma phase is likely to be present.

Mounting, Grinding, and Polishing. The techniques and equipment used for mounting, grinding, and polishing specimens of Fe-Cr-Ni heat-resistant casting alloys for metallographic examination are essentially the same as those used for wrought and cast stainless steels.

Etching. The etchants used for the Fe-Cr-Ni alloys are given in Table 10. They fall into three categories: delineating etchants (usually acid), which provide contrast and reveal general structure; staining or film-forming etchants (alkaline); and solutions for electrolytic etching.

Table 10 Etchants for microscopic examination of Fe-Cr-Ni heat-resistant casting alloys

Common name	Composition	Remarks on use
Etchants for delineating general structure		
Aqua regia	20 mL HNO_3, 60 mL HCl	Immerse specimen
Glyceregia	10 mL HNO_3, 20-50 mL HCl, 30 mL glycerol	Immerse specimen; use a hood.
Hydrochloric acid (50%)	50 mL HCl, 50 mL water	Outlines ferrite; immerse specimen
Marble's reagent	10 g $CuSO_4$, 50 mL HCl, 50 mL water	Immerse specimen
Vilella's reagent	1 g picric acid, 5 mL HCl, 100 mL ethanol	Immerse specimen
Etchants for staining or film-forming		
Alkaline hydrogen peroxide	25 mL NH_4OH, 50 mL H_2O_2 (3%), 25 mL water	Ordinarily used after a delineating etchant; immerse specimen
Alkaline potassium ferricyanide	10 g $K_3Fe(CN)_6$, 10 g NaOH, 100 mL water	Same as above
Alkaline potassium permanganate	4 g NaOH, 10 g $KMnO_4$, 85 mL water	Same as above
Alkaline sodium picrate	2 g picric acid, 25 g NaOH, 100 mL water	Same as above
Emmanuel's reagent	30 g $K_3Fe(CN)_6$, 30 g KOH, 60 mL water	Attacks sigma phase with little or no effect on carbide particles; immerse specimen
Murakami's reagent	10 g $K_3Fe(CN)_6$, 10 g KOH, 100 mL water	Stains carbide particles without staining sigma phase(a); immerse specimen
Solutions for electrolytic etching		
Ammonium hydroxide	Concentrated NH_4OH	Final electrolytic etch after etching in Vilella's reagent and in 10*N* KOH (electrolytic)
Cadmium acetate	10 g cadmium acetate, 100 mL water	Attacks $(Cr,Fe)_{23}C_6$ carbide particles
Chromic acid	2-10 g Cr_2O_3, 100 mL water	Outlines carbide particles; extracts sigma phase
Lead acetate (2*N*)	38 g $Pb(C_2H_3O_2)_2 \cdot 3H_2O$, distilled water to make 100 mL	Stains austenite, then sigma phase, then carbide particles; 1.5 V for 30 s
Oxalic acid	10 g oxalic acid, 100 mL water	Outlines carbide and sigma; 6 V, 1 to 5 s
Potassium hydroxide (1*N*)	5.6 g KOH, 100 mL water	Blackens sigma phase without outlining other phases; 1.5 V for 1 s
Potassium hydroxide (10*N*)	56 g KOH, 100 mL water	Intermediate etch between Vilella's and ammonium hydroxide (electrolytic)
Sodium cyanide	10 g NaCN, 100 mL water	Used after glyceregia; outlines carbide particles, stains sigma phase; use at 0.15 A/cm^2 (1 A/in.^{2}) for 1 to 5 s, under hood with extreme care

(a) Sometimes sigma phase is stained. Behavior must be established on a given composition.

Delineating Etchants. Glyceregia is the most widely used delineating etchant. Marble's reagent, "waterless" Kalling's reagent, and aqua regia (several modifications) are sometimes used but to a far lesser extent than glyceregia.

Staining etchants form films of reaction products on the surface of the specimen. The films exhibit color, the hue of which depends on the film thickness, which is controlled by etching time, temperature, and the etchant used. These etchants grow the films on certain second-phase constituents or on the matrix (film thickness may be a function of grain orientation, residual deformation, or composition/hardness differences). The etchants are generally aqueous solutions of potassium or sodium hydroxide with an oxidizing agent added. Picrates, potassium permanganate, hydrogen peroxide, and ferricyanides are used as oxidizing agents.

Murakami's reagent, which contains potassium hydroxide with potassium ferricyanide as the oxidizing agent, is a versatile staining etchant. By staining in different tints, it permits differentiation of several types of carbide and sigma phase. Murakami's reagent is used cold, warm, or boiling to obtain a variety of effects, but it must be used with discrimination. Because the response of the reagent indicates sensitivity to the composition of the phase being stained, a given constituent does not respond identically when it appears in alloys of different composition.

Electrolytic etching, when properly controlled, has the advantages of precision and reproducibility. Normally, the specimen to be etched is made the anode; the cathode usually is stainless steel, nickel, graphite, or platinum. The current can be supplied by one or more dry-cell batteries or a rectified power supply. Current density ranges from less than 0.15 to more than 2.0 A/cm^2 (less than 1 to more than 13 A/in.^{2}). Unmounted specimens are held with stainless steel tongs. If the specimen is mounted in a nonconducting material, the electrical connection can be conveniently made by means of a brass machine screw that contacts the underside of the specimen through a tapped hole. Or, the polished surface can be touched by a probe connected to the positive terminal.

Reference

1. W. Peter, E. Kohlhaas, and O. Jung, Revealing of Hard Metal Structures by Interference Vapor-Deposition, *Prakt Metallographie,* Vol 4, June 1967, p 284-290

Typical Microstructures of Iron-Base Alloys

Edited by George F. Vander Voort, Buehler Ltd.

Introduction

COMMONLY OBSERVED MICROSTRUCTURES in iron-base alloys (carbon and alloy steels, cast irons, tool steels, and stainless steels) occur as a result of variations in chemical analysis and processing. Comprehensive coverage of the microstructures of ferrous alloys is presented in *Metallography and Microstructures,* Vol 9, *ASM Handbook.*

A wide range of constituents (a phase or combination of two phases, in a specific configuration) are encountered in iron-base alloys. Single-phase constituents in iron-base alloys include austenite, ferrite, delta ferrite, cementite, various alloy carbides, graphite, martensite, and a variety of intermetallic phases, nitrides, and nonmetallic inclusions. Two-phase constituents include tempered martensite, pearlite, and bainite. Nonmetallic inclusions that consist of two or more phases can be present in steels. The nomenclature used to describe the constituents observed in steels has evolved over many years (see, for example, N.F. Kennon, Nomenclature in the Metallography of Steel, *J. Aust. Inst. Met.,* Vol 18 (No. 2), June 1973, p 57-73). The literature documents several names for the same constituent, which can lead to some confusion.

If only matrix phases are considered (i.e., if very small amounts of carbides, inclusions, or nitrides are ignored), the only single-phase ferrous metals or alloys are those consisting solely of ferrite, austenite, or martensite. Because as-quenched martensite is rather brittle, tempering is almost always performed before commercial utilization.

Common Constituents in Ferrous Alloys

Ferrite. Fully ferritic steels are only obtained when the carbon content is quite low. Examples include electrolytic iron, certain sheet steels, Fe-Si electrical alloys, and ferritic stainless steel. The most obvious microstructural features in such metals are the ferrite grain boundaries (Fig. 1). Ferrite is a very soft, low-strength phase. If the ferrite grain size is quite fine, good ductility and formability are obtained. Ferritic stainless steels, due to their alloy content, are not nearly as ductile as ferritic sheet steel. Because ferrite has a body centered cubic (bcc) crystal structure, ferritic metals and alloys exhibit a transition from ductile to brittle behavior as the temperature decreases or as the strain rate increases.

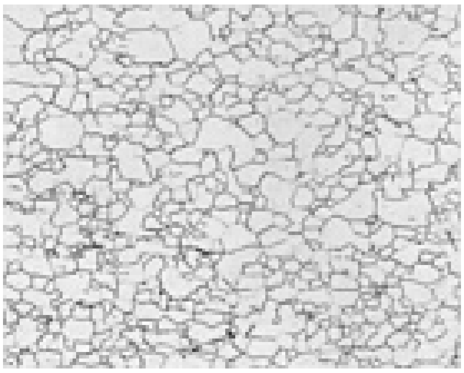


Fig. 1 Ferrite grains and grain boundaries in a low-carbon ferritic sheet steel etched with 2% nital. 100×

Austenite. Obtainment of fully austenitic steels requires careful balancing of chemical composition. In other words, rather large amounts of the austenite-stabilizing elements (carbon, nitrogen, nickel, and manganese) must be present compared with those elements that stabilize ferrite. Examples of fully austenitic ferrous alloys are austenitic stainless steels and austenitic manganese steel. Again, the most visible microstructural features of these single-phase alloys are the austenite grain boundaries. However, unlike ferritic structures, these alloys will also contain annealing twin boundaries in the wrought, solution-annealed condition (Fig. 2). Austenite is also a rather soft, low-strength phase; however, cold working produces substantial strengthening and, if extensive, may produce strain-induced martensite in some alloys. Due to their face centered cubic (fcc) crystal structures, austenitic alloys remain ductile irrespective of temperature or strain rate unless detrimental phase changes occur.

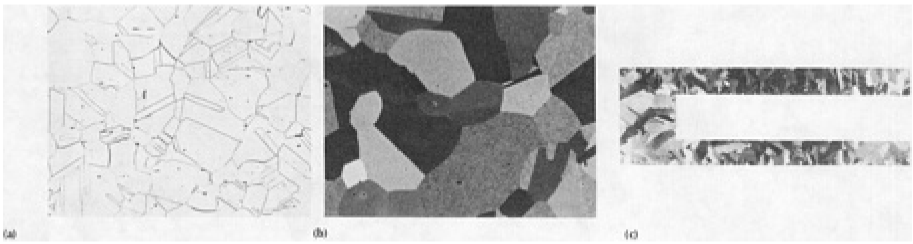


Fig. 2 Examples of fully austenitic iron-base alloys in the solution-annealed condition. (a) AISI type 316 stainless steel. Etched with HCl/HNO_3/H_2O (equal parts). 100×. (b) Hadfield's manganese steel. Etched with 2% nital (3 s) and 20% $Na_2S_2O_5$ (20 s). 100×. (c) Fe-48%Ni alloy (annealed in H_2). Etched with $FeCl_3$/HCl/H_2. 1×

Cementite, or iron carbide, contains 6.67% C (by weight), corresponding to the formula Fe_3C. In carbon and alloy steels, some of the carbide-forming elements (e.g., manganese and chromium) will replace some of the iron in cementite. Hence, the formula for cementite is often referred to as M_3C, where M stands for the carbide-forming elements present. Pure Fe_3C is quite hard (about 800 HV) and brittle. Substitution of other elements (e.g., chromium) for some of the iron in cementite will increase the hardness appreciably. Because of the brittleness of cementite, only limited amounts are present in steels. No alloy consisting solely of cementite is produced commercially. The highest cementite contents are observed in white cast irons (Fig. 3), which are used in applications where high wear resistance is desired, and the brittle nature of such alloys is not a problem.

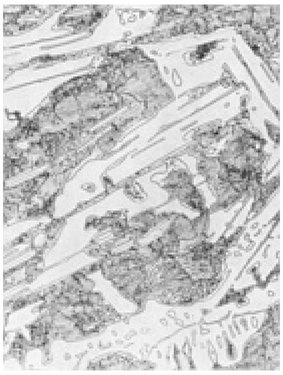


Fig. 3 Massive cementite (white) in a white cast iron specimen with a pearlitic (dark) matrix. Etched with 4% picral. 500×

Addition of carbide forming elements will result in formation of alloy carbides of various compositions depending upon the amount of the element added. These alloy carbides are generally harder than cementite. Elements that promote formation of alloy carbides include Cr, Mo, V, W, Ti, and Nb.

Graphite is a very soft, brittle phase produced in certain steels and cast irons by adjustment of chemical composition. Because cementite is not a true equilibrium phase under conditions of long-time elevated-temperature exposure, the cementite in certain carbon and alloy steels will decompose. Several tool steels are deliberately designed to produce a small amount of graphite in the structure to enhance machinability (Fig. 4). The graphite in cast irons is produced in a variety of forms, such as flake, compacted, and spheroidal. Gray cast iron containing flake graphite is quite brittle; however, if the graphite is spheroidal, as in ductile iron, good ductility is achieved. Figure 5 illustrates flake and spheroidal graphite shapes. As with cementite, graphite is only present as a minor phase, even in cast irons.

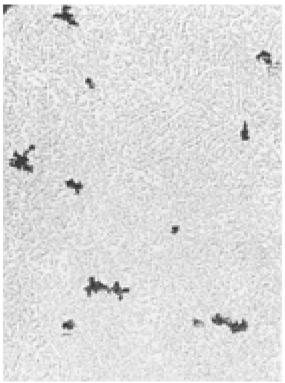


Fig. 4 Graphite in a spheroidize-annealed AISI type O6 graphitic tool steel specimen (transverse plane). The irregular black particles are graphite. The matrix is ferrite containing spheroidized cementite. Etched with 4% picral. 500×

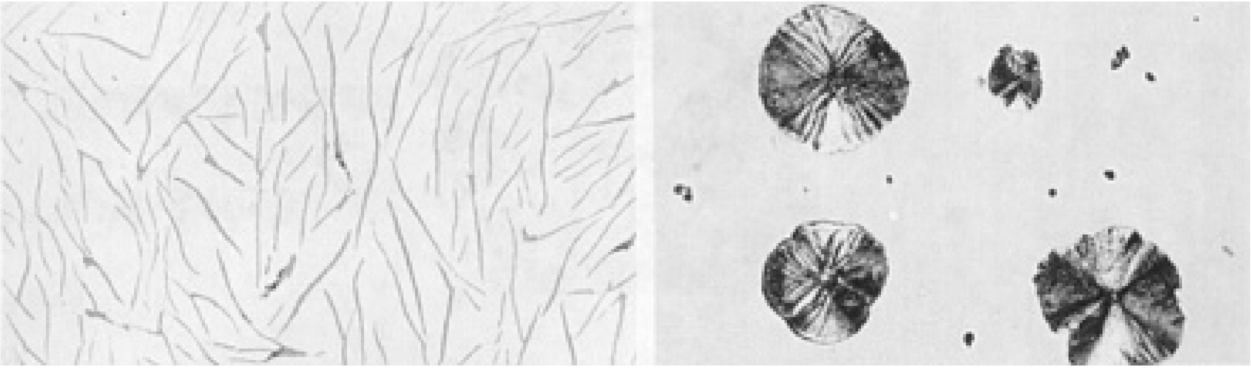


Fig. 5 Examples of two extremes in graphite shapes in cast irons. (Left) Flake graphite in gray iron. 100×. (Right) Spheroidal graphite in ductile iron (viewed in polarized light). 500×

Martensite is not an equilibrium phase in steels. Formation of martensite is dependent upon chemical composition and cooling rate from the high-temperature austenite region. Unlike other austenite transformation products, martensite forms instantaneously once the specimen is cooled below a specific temperature, known as the martensite start (M_s) temperature, which is a function of the carbon and alloy content of the parent austenite phase. The transformation is completed when the specimen reaches a lower temperature, the martensite finish temperature (M_f). The hardness of martensite is governed primarily by carbon content but is also influenced slightly by alloy content. The ability to form martensite in a steel as a function of section size and quench rate depends on the hardenability of the steel. Hardenability is increased by increasing carbon and alloy contents and by enlargement of grain size. Coarsening of grain size to improve hardenability is rarely done with wrought steels because most mechanical properties are impaired.

The nature of martensite is influenced markedly by carbon content. Basically, two types of martensite can be formed in steels. At low carbon contents, lath martensite is formed. The laths are present in a packet arrangement where the individual laths within the packet have essentially the same orientation. At high carbon contents, plate martensite is formed. The plates form as individual lenticular crystals in a wide range of sizes. Many terms have been used to denote these two types of martensite, but lath and plate are the preferred terms. At intermediate carbon contents, mixtures of lath and plate martensite are obtained. Figure 6 illustrates the appearance of lath and plate martensite; the shape of the latter is best observed when only a small amount of martensite has been formed and when the grain size is coarse.

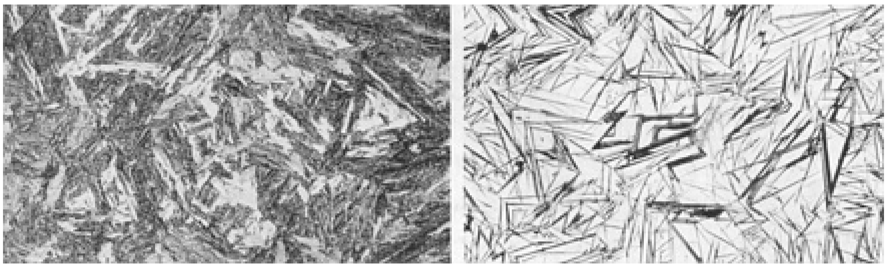


Fig. 6 Examples of lath and plate martensite. Both heat treated at higher-than-normal temperature to reveal the martensite more clearly. Both etched with 2% nital. (Left) Lath martensite in low-carbon alloy steel. 500×. (Right) Plate martensite (retained austenite matrix) in an Fe-1.4%C alloy. 200×

Because of the important influence of grain size on the properties of martensitic steels, much effort has been expended on refining the grain size of such steels. However, unlike ferritic and austenitic alloys, the critical grain size for martensitic steels is that of the parent austenite phase (i.e., the prior-austenite grain size). Delineation of the prior-austenite grain boundaries in martensitic steels by use of selective etchants is difficult but can often be achieved (Fig. 7). In general, the low-carbon martensitic steels are much more difficult to etch in this manner than medium- and high-carbon steels. In the case of lath martensite, the packet size has also been found to be an important microstructural measurement that correlates with toughness.

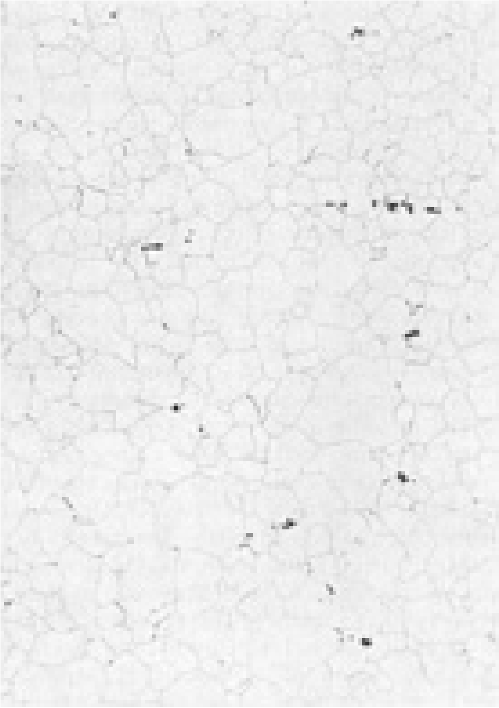


Fig. 7 Prior-austenite grain boundaries revealed by etching a heat treated medium-carbon alloy steel. Etched with saturated aqueous picric acid plus a wetting agent. 100×

As the carbon content of martensite increases, its hardness and strength increase; however, it also becomes more brittle. Martensite has a body centered tetragonal (bct) structure. The degree of tetragonality increases with carbon content. Tempering decreases the strength of martensite and increases its toughness. However, tempering of alloy steels within certain temperature ranges can reduce toughness due to embrittlement problems (temper martensite embrittlement or temper embrittlement). However, the tempering process, along with composition selections, can permit achievement of a very wide range of useful strengths and toughness, a factor that makes tempered martensite the most commercially important constituent in steels.

Tempering is a complex process from a microstructural viewpoint. In commercial practice, tempering is conducted at temperatures from about 125 °C (255 °F) to values slightly below the lower critical temperature, depending on the alloy in question and the intended application. Tempering of carbon steels is simpler than tempering of alloy steels. In the case of carbon steels, four stages have been identified.

The first stage covers the range up to about 250 °C (480 °F), where the tetragonality of the bct lattice is lost and a transition carbide, $Fe_{2.4}C$, precipitates. This carbide is extremely small and cannot be resolved by light microscopy. In the second stage, generally in the range of about 200 to 300 °C (390 to 570 °F), retained austenite (when present) decomposes. In order for retained austenite to be resolvable by light microscopy, it must be present in amounts of at least 10 to 20%--a condition obtainable only in high-carbon steels. The third stage occurs in the range of about 200 to 350 °C (390 to 660 °F) and is characterized by formation of cementite. The fourth stage occurs between about 300 °C (570 °F) and the lower critical temperature and concerns the growth of cementite to sizes visible in a light microscope and production of equiaxed ferrite grains by recrystallization. Figure 8 shows these changes for a low-carbon alloy steel, and Fig. 9 shows a high-carbon alloy steel. Neither of these grades contains enough strong carbide formers to produce more complex alloy carbides. When substantial quantities of elements, such as chromium, molybdenum, vanadium, and tungsten are present, alloy carbides are formed in the region of about 500 to 600 °C (930 to 1110 °F) along with a modest increase in hardness, termed "secondary hardening."

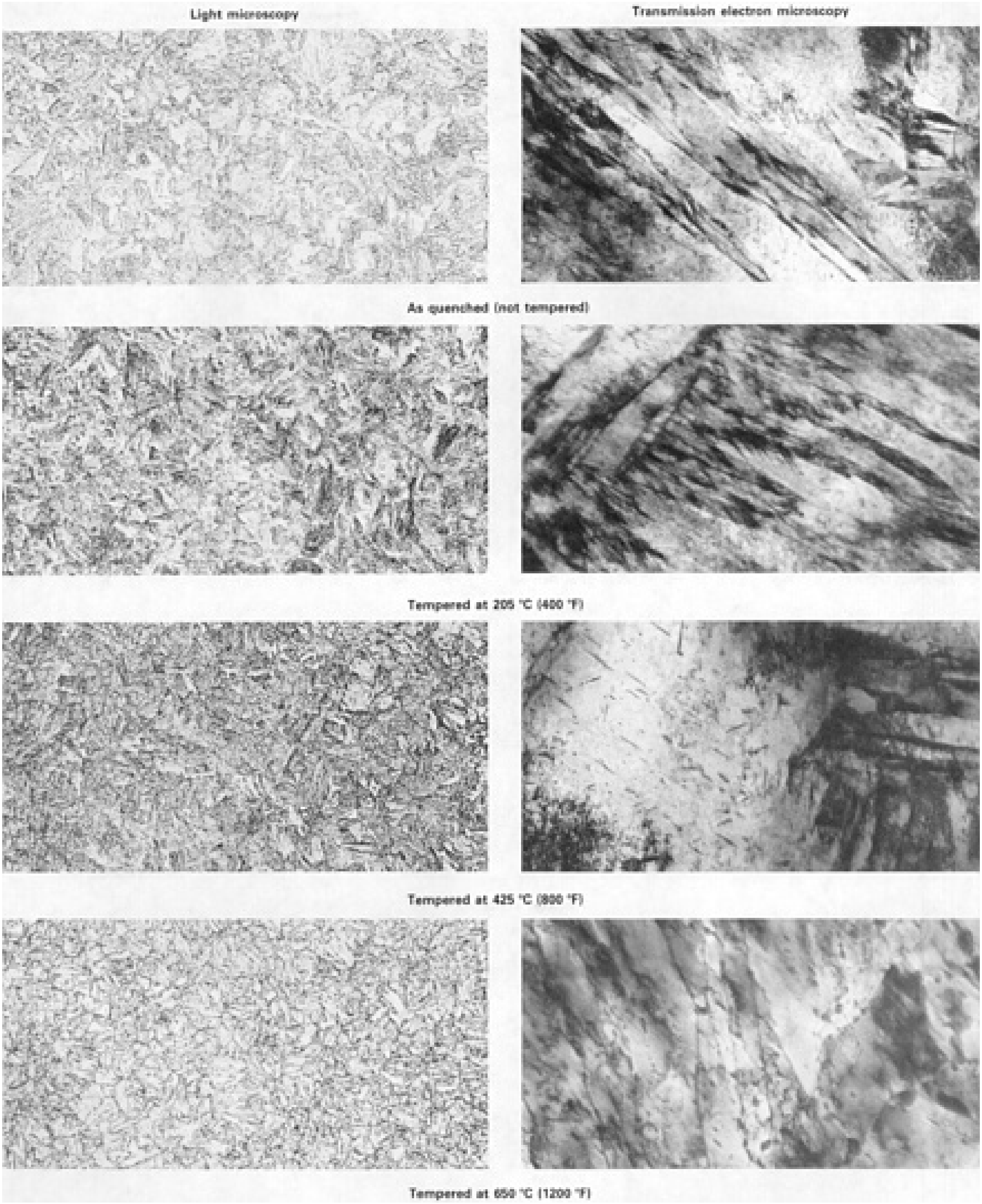
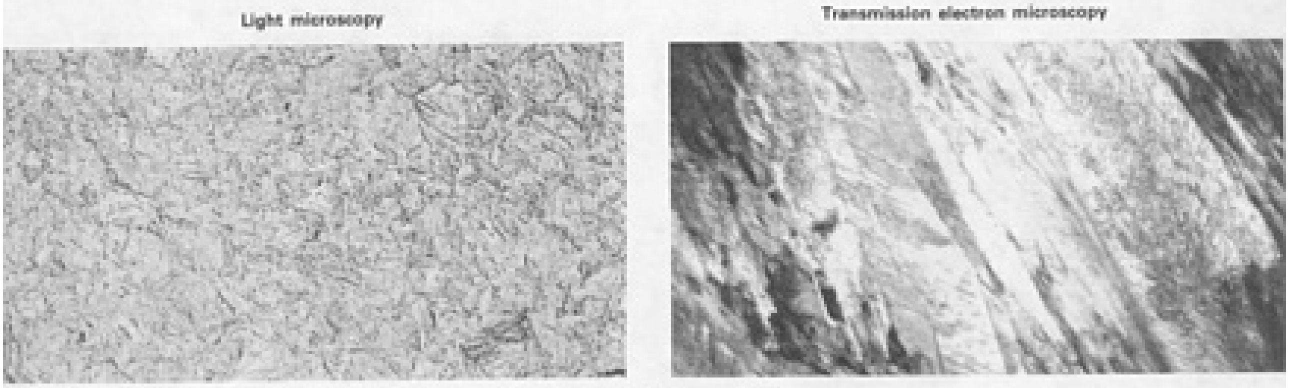
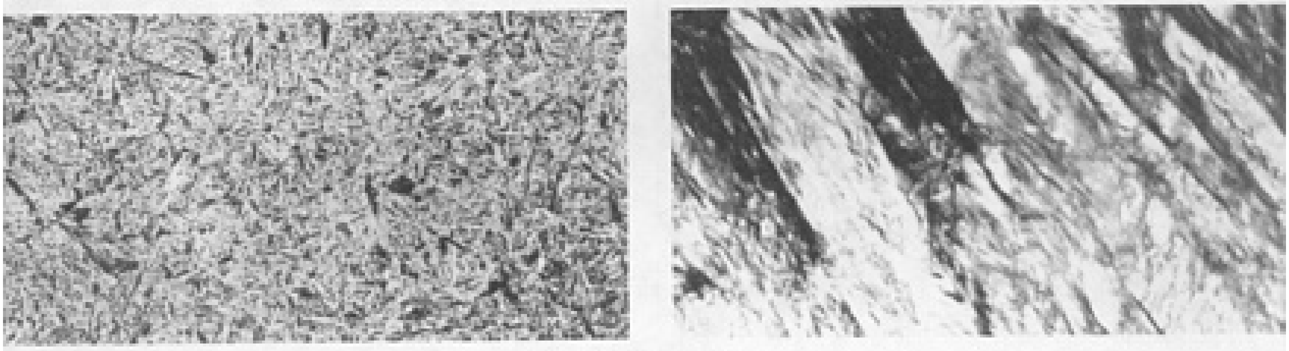

Light microscopy
Transmission electron microscopy
As quenched (not tempered)
Tempered at 205 °C (400 °F)
Tempered at 425 °C (800 °F)
Tempered at 650 °C (1200 °F)

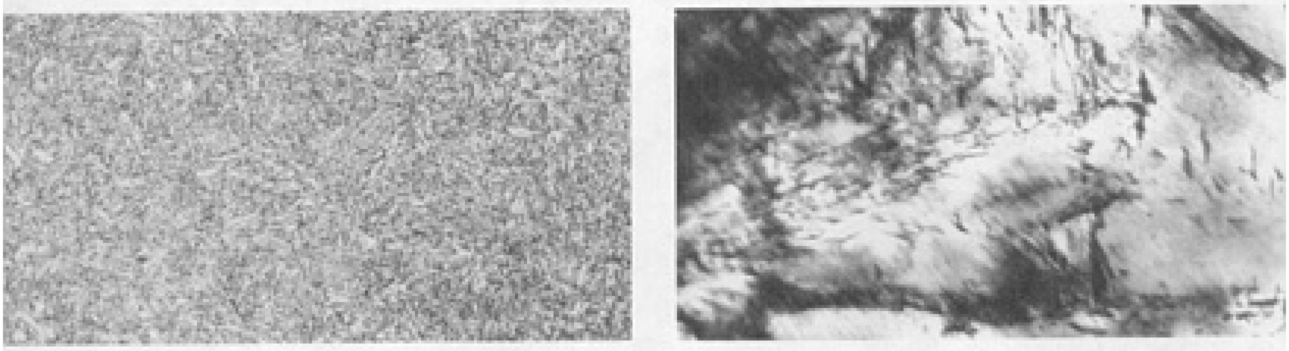
Fig. 8 Light microscopy and transmission electron microscopy (thin foil) views of AISI 8620 alloy steel after tempering at various temperatures. All specimens were water quenched from 900 °C (1650 °F) prior to tempering. Light microscopy: 2% nital, 500×; TEM: 25,000×



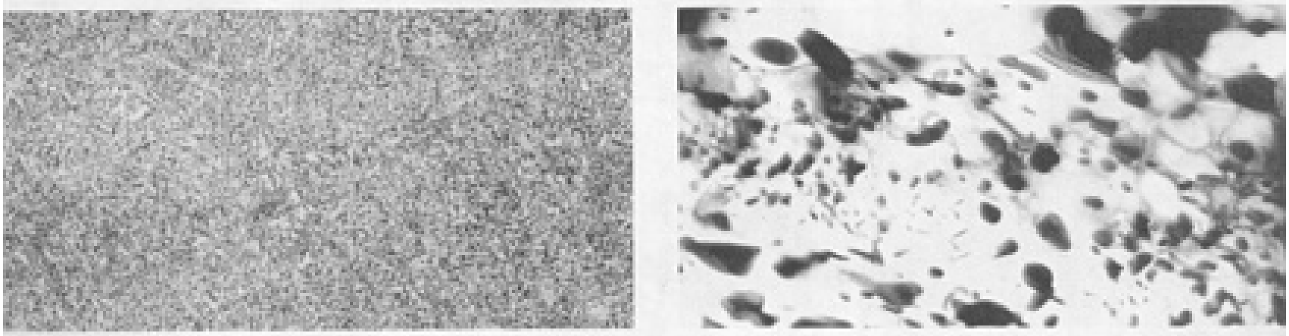
As quenched (not tempered)



Tempered at 205 °C (400 °F)



Tempered at 425 °C (800 °F)



Tempered at 650 °C (1200 °F)

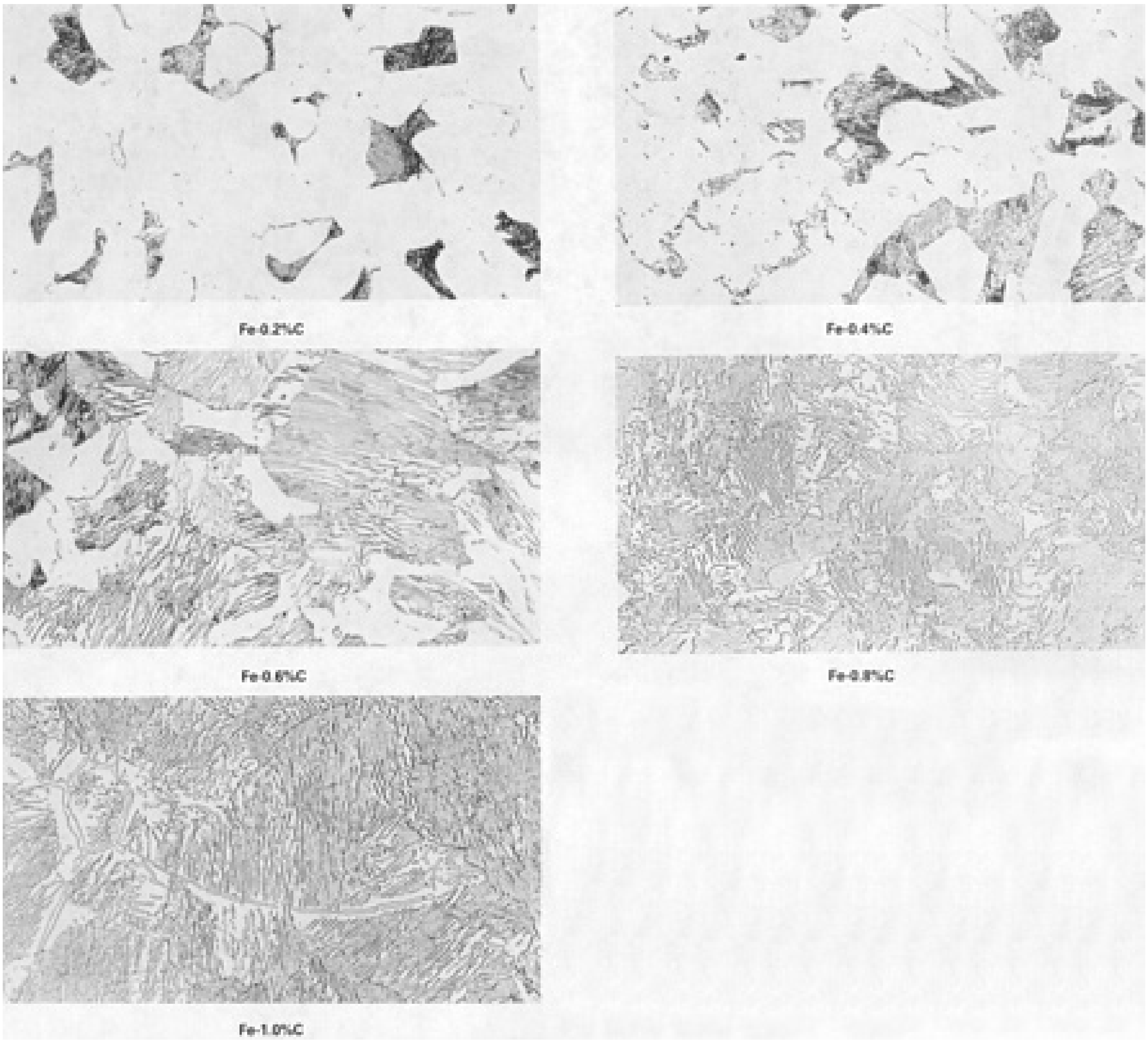
Fig. 9 Light microscopy and transmission electron microscopy (thin foil) views of AISI 5160 alloy steel after tempering at various temperatures. All specimens were oil quenched from 803 °C (1525 °F) prior to tempering. Light microscopy: 2% nital, 500×; TEM: 25,000×

Pearlite is a mixture of ferrite and cementite where the two phases are formed from austenite in an alternating lamellar pattern. Formation of pearlite requires relatively slow cooling from the austenite region. Pearlite forms at temperatures close to the lower critical temperature of the steel in question and may be formed either isothermally or by continuous cooling. As the hardenability of the steel decreases, the cooling rate can be increased without forming other constituents.

As the isothermal reaction temperature decreases or the cooling rate increases, the interlamellar spacing decreases. The strength and toughness of pearlitic steels are increased as the interlamellar spacing decreases.

For rather slow cooling rates, the relative amounts of ferrite and pearlite in carbon steels can be estimated using the iron-carbon equilibrium diagram. Knowledge that the maximum solubility of carbon in ferrite is nearly zero and a fully pearlitic microstructure is obtained when a steel containing about 0.8% C is slowly cooled from the austenite region can be used to estimate the volume fractions of ferrite and pearlite.

Figure 10 demonstrates the influence of carbon content on the amounts of ferrite and pearlite in iron-carbon alloys containing 0.2, 0.4, 0.6, 0.8, and 1.0% C. The amount of pearlite in the Fe-0.2%C alloy is simply 0.2/0.8 or 25%, and the remainder of the structure (75%) is ferrite. In like manner, the amount of pearlite in the 0.4% C alloy is 50%, and the amount in the 0.6% C alloy is 75%.


Fe-0.2%C

Fe-0.4%C

Fe-0.6%C

Fe-0.8%C

Fe-1.0%C

Fig. 10 Examples of pearlite formation in slowly cooled iron-carbon alloys as a function of carbon content. Etched with 4% picral. 500×

In these alloys, the ferrite forms prior to the eutectoid reaction (which produces the pearlite) and is termed "proeutectoid ferrite." Below about 0.4% C, the proeutectoid ferrite forms as equiaxed patches and is the continuous phase. Above about 0.4% C, the proeutectoid ferrite generally exists as isolated, equiaxed patches or as a grain-boundary layer.

Carbon steels are referred to as hypoeutectoid, eutectoid, or hypereutectoid when carbon contents are below 0.8%, about 0.8% or above 0.8%, respectively. In the case of hypereutectoid steels, such as the Fe-1%C alloy (Fig. 10), excess cementite above the amount required to form pearlite will precipitate in the austenite grain boundaries prior to the eutectoid reaction. This excess cementite is referred to as "proeutectoid cementite." A grain-boundary cementite network renders such steels quite brittle.

The strength and hardness of ferrite-pearlite steels increase with increasing pearlite content and are further increased by reductions in the interlamellar spacing. Pure ferrite (no carbon) has a hardness of about 70 HV, whereas very fine pearlite in a eutectoid carbon steel has a hardness of nearly 400 HV. Fine pearlite is the most desirable structure for wire drawing, where extremely high strengths can be obtained. Figure 11 shows the microstructures of cold drawn low-carbon and high-carbon wire (longitudinal views).

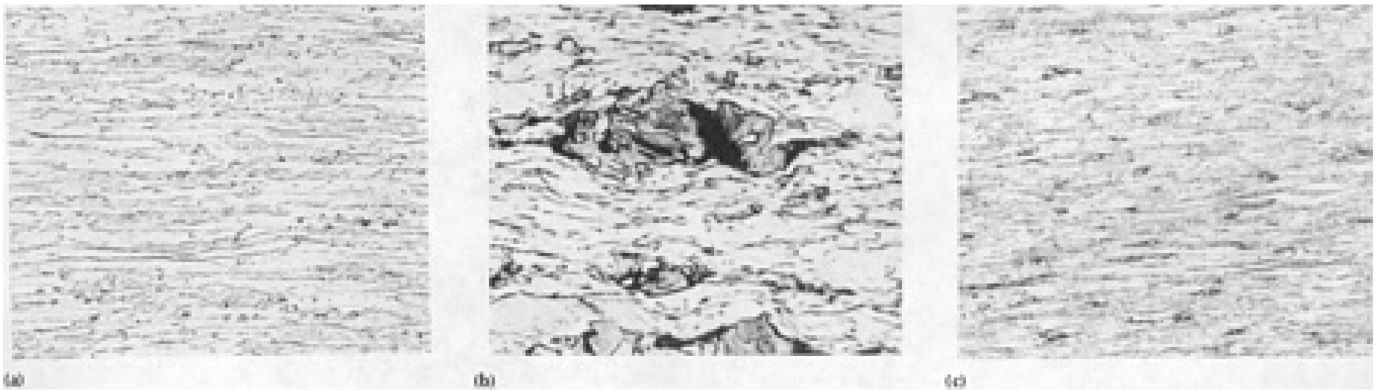


Fig. 11 Examples of cold worked carbon steel microstructures (longitudinal planes; etched with 2% nital). (a) AISI 1008, 500×. (b) AISI 1020, 1000×. (c) AISI 1080, 500×

Carbon steels are widely utilized in the hot-rolled condition. The austenite grain size of the steel as it enters the final rolling pass establishes the relative sizes of the ferrite and pearlite produced during subsequent air cooling. On the other hand, the cooling rate influences the fineness of the pearlite, the morphology of the proeutectoid ferrite, and the amounts of the various constituents. Figure 12 shows the influence of austenite grain size on the sizes, shapes, and amounts of ferrite and pearlite, where an AISI 1040 carbon steel has been air cooled from 900, 980, and 1095 °C (1650, 1800, and 2000 °F).

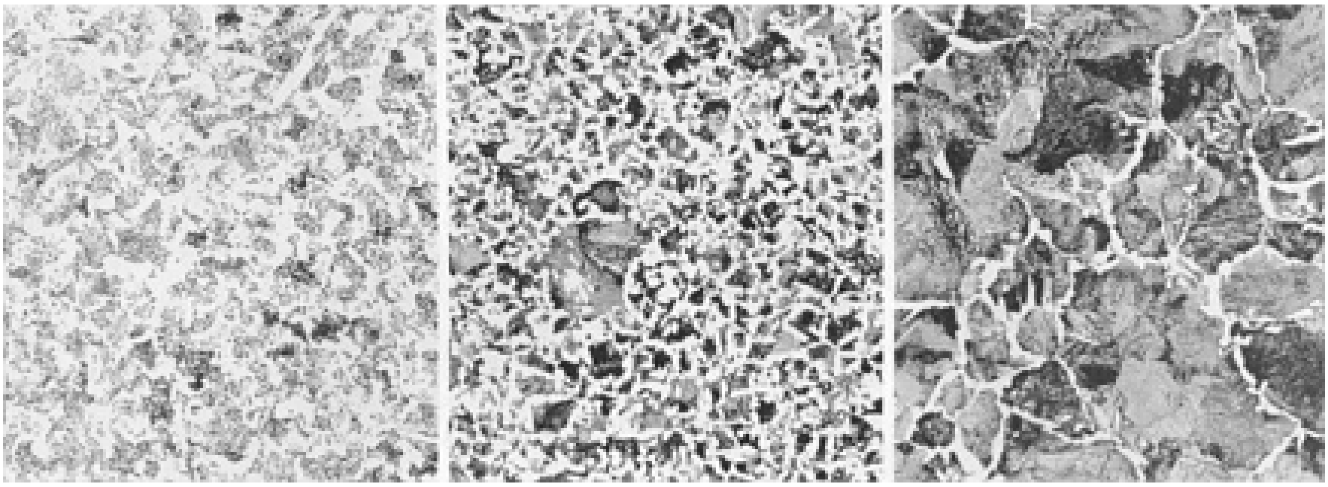


Fig. 12 The influence of austenitizing temperature on the amount, size, and fineness of the transformation products, ferrite and pearlite, of normalized AISI 1040 carbon steel. (Left) Austenitized at 900 °C (1650 °F), air cooled. (Center) Austenitized at 980 °C (1800 °F), air cooled. (Right) Austenitized at 1095 °C (2000 °F), air

cooled. All etched with 4% picral. 200×

To obtain maximum ductility and formability, carbon steels may be subjected to a special annealing treatment that spheroidizes the cementite. This treatment is commonly used on tool steels to improve their machinability. To best observe the spheroids of cementite, specimens of steels so treated should be etched with 4% picral, which reveals the ferrite/carbide interfaces but not the ferrite grain boundaries. Figure 13 illustrates this problem of structure visibility using a spheroidized low-carbon steel. Etching with 2% nital obscures the spheroidized cementite. As the carbon content increases, the volume fraction of cementite increases. Figure 14 shows the microstructure of spheroidized AISI W2 (1.1% C) tool steel.

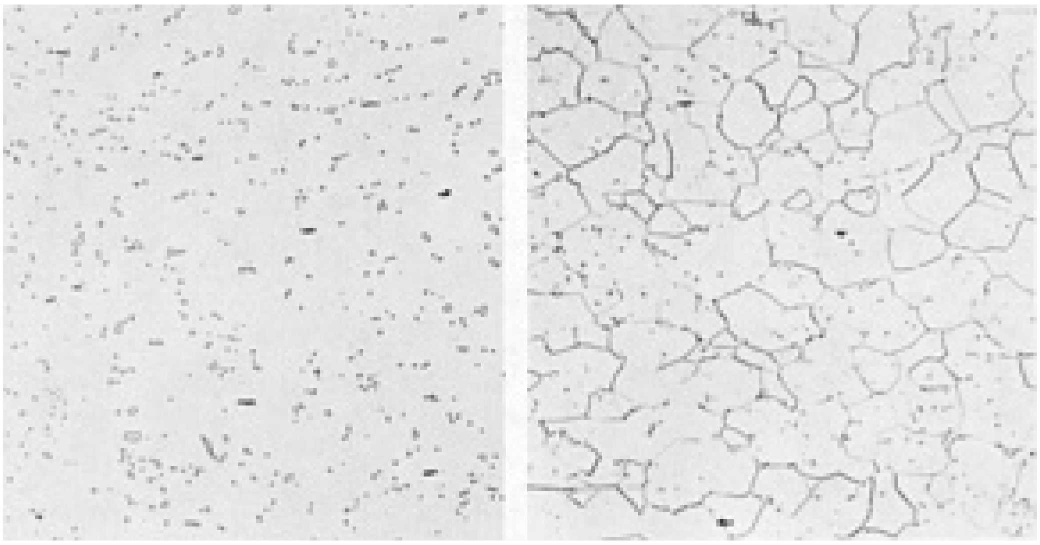


Fig. 13 Influence of etchant upon the ability to observe spheroidized cementite in AISI 1008 sheet steel. (Left) Etched with 4% picral. (Right) Etched with 2% nital. 500×

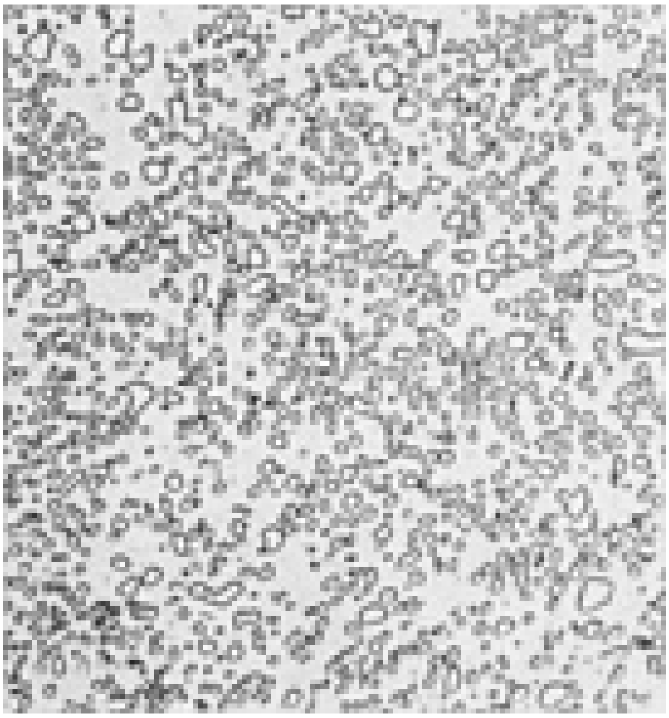


Fig. 14 Spheroidized cementite in AISI W2 carbon-vanadium (1.10% C) tool steel. Etched with 4% picral.

1000×

Bainite, an austenite transformation product, is a lathlike aggregate of ferrite and cementite that forms under conditions intermediate to those that result in formation of pearlite and martensite. Bainite is commonly classified as either upper bainite or lower bainite. Upper bainite forms either isothermally or during continuous cooling at temperatures just below those that produce pearlite. Lower bainite forms at still lower temperatures, down to the M_s temperature, or slightly below in certain cases.

Formation of upper bainite (Fig. 15) begins by growth of long ferrite laths that are devoid of carbon. Because the carbon content of the ferrite laths is very low, the austenite at the lath boundaries is enriched in carbon. The shape of the cementite formed at the lath boundaries varies with carbon content. In low-carbon steels, the cementite will precipitate as discontinuous stringers and isolated particles, whereas at higher carbon contents the stringers are more continuous. In some instances, carbide is not precipitated but is retained as austenite or transforms to plate martensite.

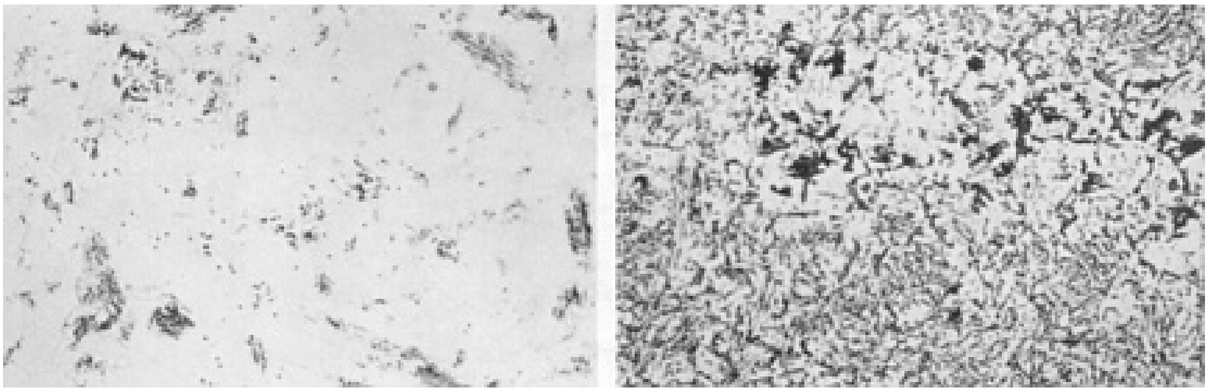


Fig. 15 Upper bainite formed isothermally at 480 °C (900 °F) in AISI 4142 alloy steel. (Left) 845 °C; 480 °C for 30 s; water quenched. (Right) 845 °C; 480 °C for 2 h; water quenched. Both etched with 4% picral. 1000×

Lower bainite (Fig. 16) has a more acicular appearance compared with that of upper bainite. The ferrite plates are broader than those in upper bainite and are more similar in appearance to plate martensite. As with upper bainite, the appearance of lower bainite varies with carbon content. Lower bainite is characterized by formation of rodlike cementite or $Fe_{2.4}C$ (depending on the transformation temperature or steel composition) within the ferrite plates.

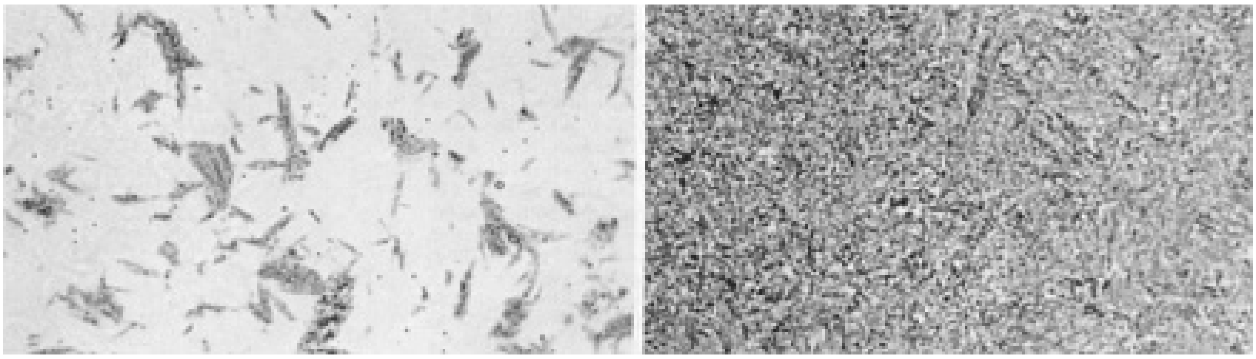


Fig. 16 Lower bainite formed isothermally at 370 °C (700 °F) in AISI 4142 alloy steel. (Left) 845 °C; 370 °C for 60 s; water quenched. (Right) 845 °C; 370 °C for 30 min; water quenched. Both etched with 4% picral. 1000×

Nonmetallic inclusions in steel are either indigenous or exogenous in origin. Indigenous inclusions form as a natural result of the decrease in solubility of oxygen or sulfur that occurs as the metal freezes. Exogenous inclusions are introduced from external sources (e.g., slag or refractories) that enter the steel and become trapped during solidification. In most instances, these included phases are undesirable.

There are, however, two basic types of ferrous alloys that are deliberately made with additions of either exogenous or indigenous inclusions. Wrought iron (Fig. 17) is made by mixing together slag and relatively pure iron. In the hot worked condition, the slag becomes elongated, thus promoting considerable anisotropy. The toughness of wrought iron is very good if the crack is perpendicular to the fiber axis but very poor if it is parallel to the fiber axis. Free-machining steels are a classic example of the deliberate addition of indigenous inclusions, most commonly manganese sulfide, to enhance machinability. Figure 18 illustrates the appearance of MnS in a free-machining steel. Some free-machining steels are also given deliberate additions of either lead or bismuth. Both of these elements are virtually insoluble in solid steel and exist as small elemental globules often associated with the sulfides.

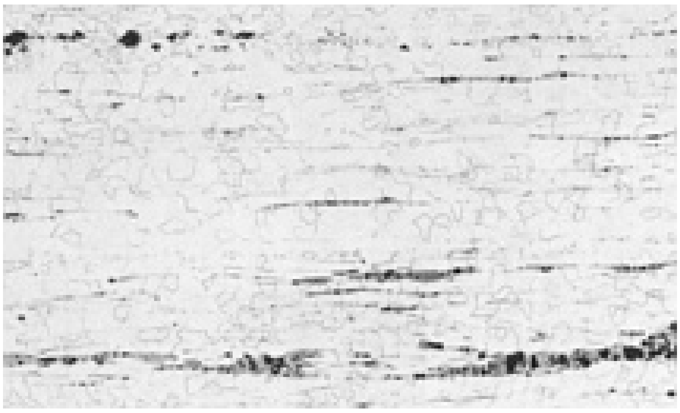


Fig. 17 Microstructure of wrought iron (longitudinal plane). Etched with 2% nital. 50×

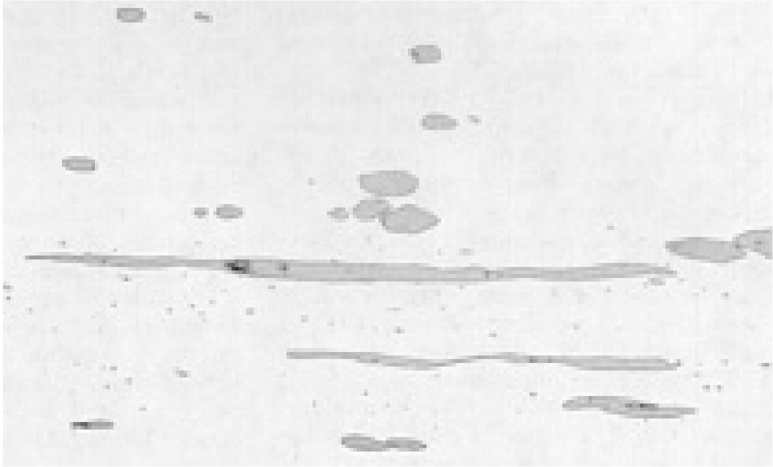


Fig. 18 Manganese sulfide inclusions in wrought AISI 1214 free-machining carbon steel (longitudinal plane). 200×

Manganese sulfides precipitate in different forms depending primarily on the oxygen content of the steel. Very high oxygen contents (low carbon contents, no strong deoxidizers) promote formation of large, globular, isolated manganese sulfides referred to as type I sulfides. Type I sulfides generally are desirable in free-machining steels. Lower oxygen contents and moderate deoxidation, particularly by small amounts of aluminum, promote precipitation of sulfides in a fanlike or chainlike pattern at the grain boundaries; these sulfides are referred to as type II sulfides. Type II sulfides are most detrimental to toughness and ductility. Very low oxygen contents and strong deoxidation by aluminum promote formation of small, angular, dispersed sulfides, referred to as type III sulfides. These are less harmful to properties than are type II sulfides. Figure 19 illustrates these three classic sulfide forms, which are most easily observed in the as-cast condition. Other more complex types of sulfides can be produced due to the addition of other elements that influence sulfide composition and the precipitation reaction (e.g., calcium and rare earth elements).

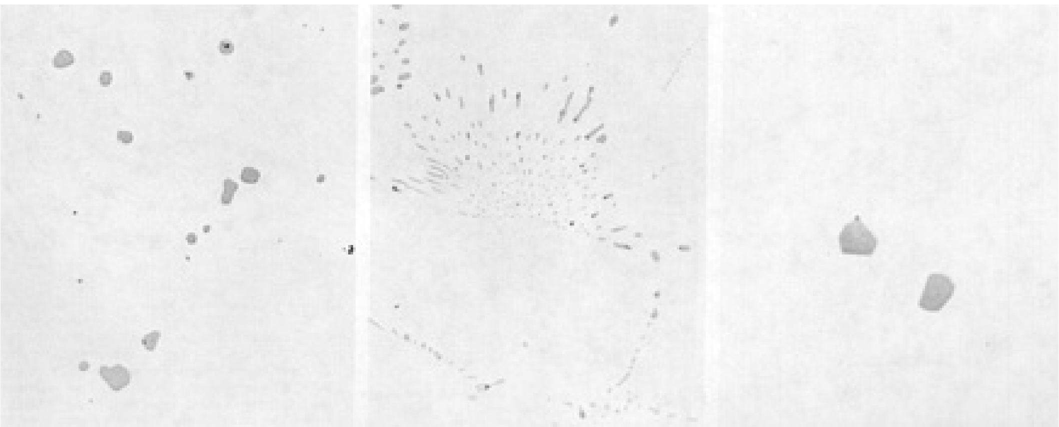


Fig. 19 Examples of the three most common forms of manganese sulfides viewed in the as-cast condition. (Left) Type 1; 250×. (Center) Type II; 250×. (Right) Type III; 1600×

Examples of Complex Mixtures of Constituents

The micrographs previously presented show many of the more common complex mixtures of microstructures in ferrous alloys. There are a few others, however, that deserve mention. Figure 20, for example, shows the microstructure of a dual-phase sheet steel that was austenitized in the two-phase region and then slowly cooled. The white matrix phase is ferrite, the small outlined white particles are retained austenite, and the small dark patches are auto-tempered martensite (and a minor amount of retained austenite). A large nitride particle is also shown at the bottom of the field.

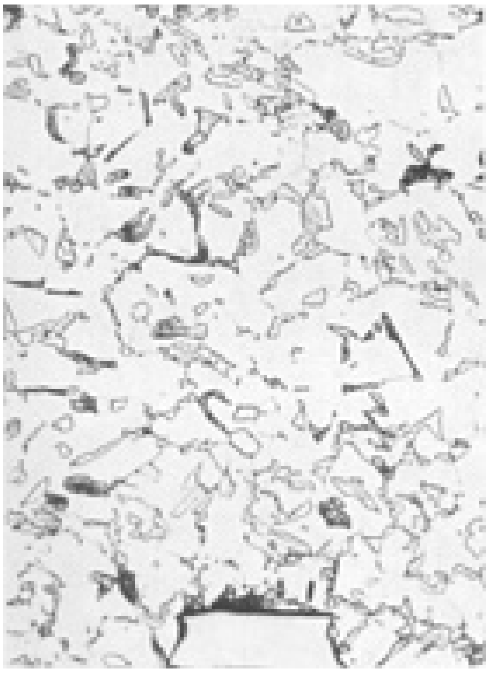


Fig. 20 Microstructure of heat treated dual-phase low-carbon sheet steel. Etched with 20% $Na_2S_2O_5$ in H_2O. 1000×

The higher alloy, high-carbon tool steels contain undissolved alloy carbides in a matrix of tempered martensite after commercial heat treatment. When properly heat treated, many of these alloys also contain small amounts of retained austenite, although such amounts are usually too low to be resolved by light microscopy, unless an excessively high austenitizing temperature was used by error. Figure 21 shows two such alloys: AISI D2 and M2 tool steels. Both were austenitized at the recommended temperatures and then tempered. The white outlined particles are the alloy carbides, also called primary carbides, and the matrix is tempered martensite plus a small amount of retained austenite not visible by light microscopy. Because these specimens were tempered at relatively low temperatures, the prior-austenite grain boundaries are visible after etching.

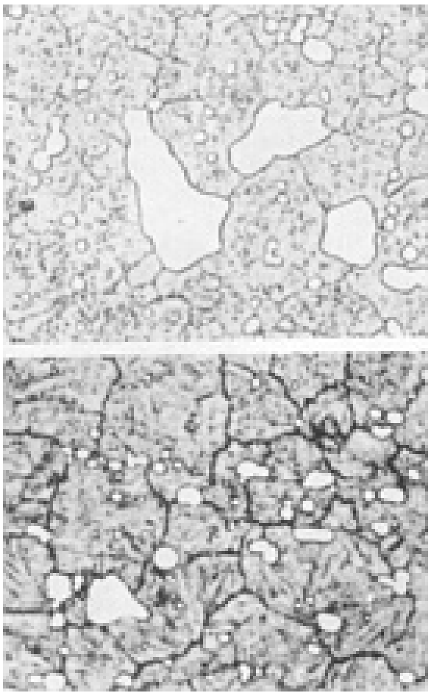


Fig. 21 Microstructure of two common high-carbon, high-alloy tool steels in the heat treated condition. (Top) AISI D2 tool steel. Etched with 4% picral plus HCl. (Bottom) AISI M2 tool steel. Etched with 10% nital. 1000×

Stainless steels can also exhibit a wide range of complex structures that can be even more complex after long-time, high-temperature exposure (Fig. 22). AISI type 440C martensitic stainless steel contains undissolved alloy carbides in a high-carbon martensitic matrix (some retained austenite is also present but cannot be resolved by light microscopy). The AISI type 304 austenitic weld metal contains delta ferrite, which prevents hot cracking. The 17-4 PH (precipitation-hardening) stainless steel contains delta ferrite stringers in a low-carbon martensitic matrix. The duplex stainless steel (as cast and annealed) contains austenite in a ferritic matrix.

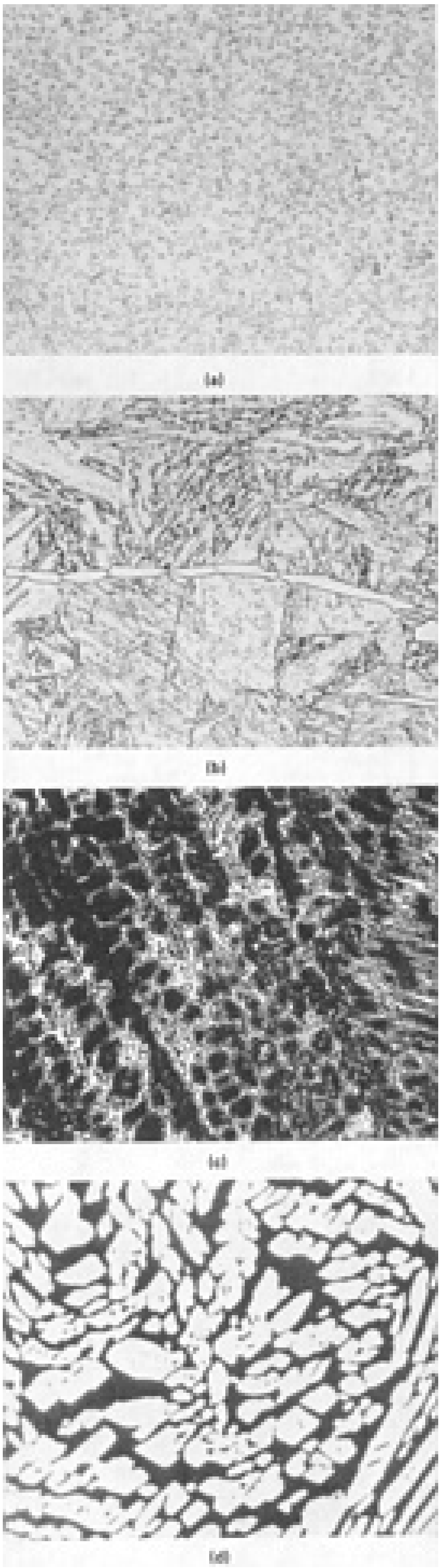


Fig. 22 Examples of two-phase stainless steels with various microstructural combinations. (a) AISI 440C, annealed. Structure: ferrite and carbides. Vilella's reagent; 500×. (b) 17-4 PH, solution annealed and aged. Structure: martensite and delta ferrite (white). Fry's reagent; 500×. (c) Austenitic AISI 304, welded. Structure: delta ferrite and austenite (dark). Heat tinted; 500×. (d) Duplex alloy, as cast and annealed. Structure: austenite and ferrite (dark). Tint etched; 200×

Various surface treatments can also be applied to ferrous alloys to produce considerable microstructural complexity at the treated surface. These processes can simply involve the application of sufficient heat to austenitize and subsequently harden the surface, as in flame hardening or induction hardening. Hardened surface layers may also be formed when low-hardenability carbon tool steels are water or brine quenched. The net result of these treatments is a martensitic surface layer and an unhardened core with a transition layer between them. The transition-layer microstructure may be more complex for flame- or induction-hardened specimens than for quenched carbon tool steels.

Other processes are also utilized that change the composition of the surface layer so as to develop unique combinations of properties, such as a strong and highly wear-resistant surface on a more-ductile, lower-strength core. The most common treatments used to produce these effects are carburizing, nitriding, and carbonitriding. These practices are usually applied to low- or medium-carbon steels. Figure 23 shows the carburized surface of a low-carbon steel. At the extreme surface, the carbon content is above the eutectoid carbon content and a grain-boundary cementite layer is observed. Beneath this zone, the structure is fully pearlitic. At still greater depths, the amount of pearlite decreases until the matrix is reached. This specimen was cooled slowly after carburizing. Before such a steel would be placed in service, it would be heat treated to form martensite in the carburized case.

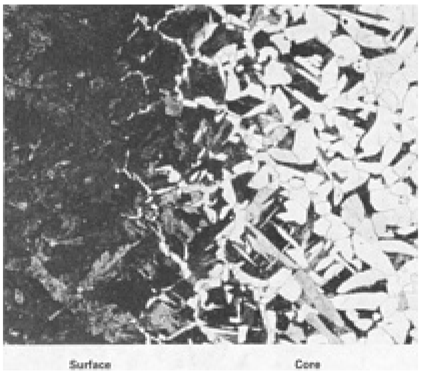


Fig. 23 Microstructures at the surface and core of carburized AISI 1020 carbon steel slowly cooled from the carburizing temperature. 2% nital; 200×

Nitriding is commonly performed on medium-carbon alloy steels that have been austenitized, quenched, and tempered between about 540 and 620 °C (1000 and 1150 °F). Nitriding is generally performed at temperatures slightly below this range for rather long times compared with those used for carburizing. Diffusion of nitrogen into the surface layer produces iron nitrides, which promote high surface hardness and beneficial residual compressive stresses. Figure 24 shows a nitrided specimen of AISI type 4150 steel on which a rather thick surface layer of undesirable, brittle iron nitride has formed.

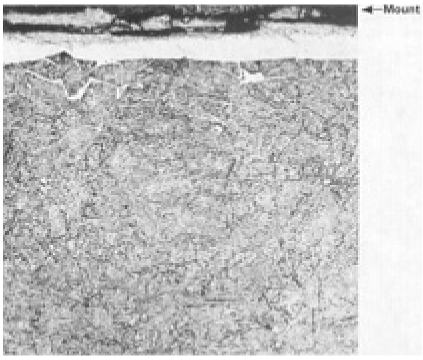


Fig. 24 Microstructure at the surface of a heavily nitrided AISI 4150 alloy steel that was heat treated prior to nitriding. Note the heavy iron nitride "white" layer and grain-boundary penetration at the surface. 4% picral, 200×

Decarburization due to improper control of the furnace atmosphere also produces a variation in surface microstructure. Figure 25(a) shows a partially decarburized surface layer on hot-rolled AISI type 9260 mod spring steel. The white layer at the surface is nickel plating (applied for edge protection). The gray layer beneath the nickel plating is scale. The decarburized surface contains a range of ferrite and pearlite, and the matrix is nearly all pearlite. The other two micrographs in Fig. 25 show decarburization on hardened AISI 5160H and 5160 mod spring steels. The view at the center shows a very minor loss of carbon on a bar whose surface was turned prior to heat treatment. No free ferrite is present. The structure at the surface is a mixture of bainite and martensite. Figure 25(c) shows a thick layer of free ferrite (total loss of carbon) with a columnar grain structure after heat treatment. Note the narrow zone beneath the free ferrite, where the structure changes gradually to all martensite.

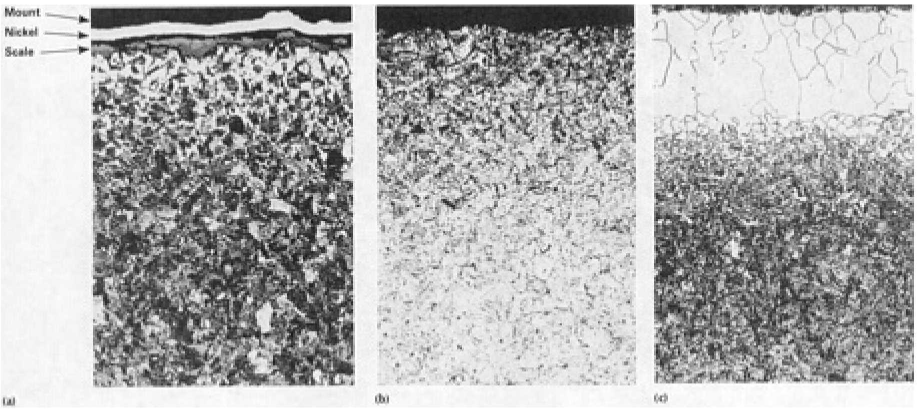


Fig. 25 Examples of different degrees of decarburization in spring steels. (a) Partial decarburization of as-rolled AISI 9260 mod spring steel that was nickel plated edge protection. (b) Partial decarburization of hardened AISI 5160H spring steel whose surface was turned prior to hardening (no protective atmosphere). (c) Complete decarburization of hardened AISI 5160 mod spring steel that was given no surface preparation prior to hardening (no protective atmosphere). All specimens etched with 2% nital. 200×

The examples in this article represent many of the microstructures commonly encountered in ferrous alloys. The natures of the structures present depend on the composition of the alloy and the manner of processing. To reveal these constituents clearly, the specimens must be properly prepared and etched with the reagent most appropriate for the constituents present.

Metallographic Technique for Nonferrous Metals and Special-Purpose Alloys

Edited by George F. Vander Voort, Buehler Ltd.

Technique for Aluminum Alloys

ALUMINUM ALLOYS encompass a wide range of chemical composition and, as a result, a fair range of hardness; consequently, there is considerable variation in the techniques required for metallographic preparation and examination. The softer alloys generally are more difficult to prepare by mechanical polishing, because deformation caused by cutting and grinding extends to a greater depth. Embedding of abrasive particles in the metal during polishing is more likely, and relief between the matrix and second-phase particles, which are much harder than the matrix, will develop more readily during polishing.

Metallography on the Macroscopic Scale

The same principles of preparation for macroscopic examination apply to aluminum alloys as to metals in general.

Chemical Preparation. Removal of cutting oils and other greasy contaminants from aluminum surfaces before etching is a wise precaution but not always necessary. The caustic etch (etchant 1 in Table 1) is, in itself, an excellent degreaser. The acidic etchants are more likely than the caustic etch to act in an uneven manner if the surface is not precleaned. Table 1 lists a selection of etchants and etching methods that will accomplish all necessary tasks of preparing specimens for macroexamination. Table 2 indicates the etchants in Table 1 that are most applicable to various classes of alloys. If Table 1 presents a choice between caustic and mixed-acid etching, the selection should be based on the primary purpose of the examination.

Table 1 Etchants for use in macroscopic examination of aluminum alloys

See Table 2 for applicability to specific alloys.

Etchant	Composition (parts are by volume)	Procedure for use
1 Caustic etch	10 g NaOH to each 90 mL water	Immerse specimens 5 to 15 min in solution heated to 60 to 70 °C (140 to 160 °F)[(a)], rinse in water, dip in 50% HNO_3 solution to desmut, rinse in water, dry.
2 Tuckers's reagent	45 parts HCl (conc), 15 parts HNO_3 (conc), 15 parts HF (48%), 25 parts water	Mix fresh before using. Immerse or swab specimen for 10 to 15 s, rinse in warm water, dry, and examine for desired effect. Repeat as much as necessary until desired effect is obtained.
3	1 part HF (48%), 9 parts water	Requires fairly smooth surface. Immerse until desired effect is obtained, hot-water rinse, dry.
4 Poulton's reagent	12 parts HCl (conc), 6 parts HNO_3 (conc), 1 part HF (48%), 1 part water	May be premixed and stored for long periods [(b)]. Etch by brief immersion or by swabbing. Rinse in cool water, and do not allow either the etchant or the specimen to heat up during etching.
5	50 parts HCl (conc), 15 parts HNO_3 (conc), 3 parts HF (48%), 5 parts $FeCl_3$ solution (conc)	Mix fresh before use. Cool solution to 10 to 15 °C (50 to 60 °F) with jacket of cold water. Immerse a few seconds, rinse in cold water; repeat until desired effect is obtained.

(a) This etchant may be used without being heated, but the etching action will be slower.

(b) Solution should be stored in a vented container, preferably under a fume hood, to prevent buildup of gas pressure. The container should be made of polyethylene or be lined with wax.

Table 2 Applicability of etchants in Table 1 to macroexamination of aluminum alloys

Alloy	Etchant
High-purity aluminum	4 or 5
Commercial-purity aluminum: 1*xxx* series	4, 2, or 1
All high-copper alloys: 2*xxx* series and casting alloys	1
Al-Mn alloys: 3*xxx* series	4, 2, or 1
Al-Si alloys: 4*xxx* series and casting alloys[(a)]	4, 2, or 3
Al-Mg alloys: 5*xxx* series and casting alloys	4, 2, or 1
Al-Mg-Si alloys: 6*xxx* series and casting alloys	4, 2, or 1
Al-Cu-Mg-Zn alloys: 7*xxx* series and casting alloys	1

(a) Also, welds and brazed joints made with the use of these alloys as filler metals

Metallurgy on the Microscopic Scale

The determination of the best procedure for microscopic examination is governed by the same considerations as in macroscopic examination, but the area that can conveniently be examined is usually more limited.

Mounting in a plastic medium to form a cylindrical piece is the generally accepted procedure, unless the specimen is of such dimensions that it can easily be hand held for subsequent grinding and polishing. In general, details given in the general section on mounting apply here as well. Special problems relating to choice of mounting method or material may have many causes:

- The inclusion of alloys of greatly dissimilar hardness in the same mount
- The need for preservation of flatness to the very edge
- The need to mount thin sheet specimens that must be polished in a plane perpendicular to the rolled surface
- The need for connecting electrical leads to one or more specimens for subsequent electropolishing or electrolytic etching

Grinding and Rough Polishing. Because aluminum and its alloys are relatively soft compared with many other metals, most abrasives are satisfactory for grinding, although SiC papers are most commonly used. In the traditional approach, grinding progresses through the standard sequence of grit sizes (i.e., 120, 240, 320, 400, and 600 grit). For control of relief, it is possible to use grinding paper with still finer grits. Rough polishing follows, using a napless or low-nap cloth for relief control or a medium-nap cloth if relief is not a problem. The most commonly used abrasive for rough polishing is 6 μm diamond.

Final Polishing. Historically, the most commonly used final-polishing medium for aluminum alloys has been a pure grade of magnesium oxide powder, used on a medium-nap or short-nap cloth of uniform texture. The abrasive is rendered pastelike by applying about a teaspoonful near the center of the cloth and moistening it with distilled or deionized water, working it to a proper consistency with the finger. A low wheel speed, 50 to 80 rpm, is required for final polishing. High hand pressure and frequent rotation of the specimen are used for the first few minutes, and only enough water is added to avoid dryness and pulling of the specimen by the cloth. Gradually, pressure is relaxed and more water is added to wash away excess abrasive. Toward the end of the polish, copious quantities of water can be used to remove all abrasive, and the polishing cloth, in effect, serves to wipe the specimen clean. Residual abrasive may be removed by lightly applying a clean, wet cotton swab.

In recent years, high quality MgO has been difficult to obtain, and MgO always presents problems in its use. Basic colloidal silica polishing suspensions have been found to be highly effective for final polishing of aluminum and its alloys and have largely replaced use of magnesia abrasives.

Etching for Microscopic Examination. Microscopic examination of the polished specimen before etching is always advisable, because etching can obscure as well as reveal important details, such as incipient melting, fine cracks, and nonmetallic inclusions. Table 3 gives a selection of etchants that encompass all ordinary purposes of microscopic examination of commercial aluminum alloys. Table 4 describes these purposes and suggests etchants that are most likely to be successful on various classes of alloys. Often, it may be possible to apply a second etch directly over the first, without repolishing, as dictated by experience. A general rule of thumb is that the etchants that reveal grain structure are the most aggressive and should be applied last.

Table 3 Etchants for use in microscopic examination of aluminum alloys

See Table 4 for applicability to specific alloys

Etchant	Composition	Procedure for use
1 Hydrofluoric acid etch	1 mL HF (48%), 200 mL water	Swab for 15 s, or immerse for 30 to 45 s
2	1 g NaOH, 100 mL water	Swab for 5 to 10 s
3A Keller's reagent	2 mL HF (48%), 3 mL HCl (conc), 5 mL HNO_3 (conc), 190 mL water	Immerse for 8 to 15 s, wash in stream of warm water, blow dry. Do not remove etching products from surface
3B Dilute Keller's reagent	20 mL etchant 3A, 80 mL water	Mix fresh before using. Immerse specimen for 5 to 10 s
4 Modified Keller's reagent	2 mL HF (48%), 3 mL HCl (conc), 20 mL HNO_3 (conc), 175 mL water	Immerse for 10 to 60 s, wash in stream of warm water, blow dry. Do not remove etching products from surface.
5 Barker's reagent	4 to 5 mL HBF_4 (48%), 200 mL water	Electrolytic: use Al, Pb, or stainless steel for cathode; specimen is anode. Anodize 40 to 80 s at about 0.2 A/cm^2 (about 20 V dc). Check results on microscope with crossed polarizers.
6	25 mL HNO_3 (conc), 75 mL water	Immerse at 70 °C (160 °F) for 45 to 60 s
7	20 mL H_2SO_4 (conc), 80 mL water	Immerse at 70 °C (160 °F) for 30 s; rinse in cold water.
8	10 mL H_3PO_4 (85%), 90 mL water	Immerse at 50 °C (120 °F) 1 min, or 3 to 5 min (see Table 4)
9	5 mL HF (48%), 10 mL H_2SO_4, 85 mL water	Immerse for 30 s
10	4 g $KMnO_4$, 2 g Na_2CO_3, 94 mL water, few drops wetting agent	Specimen surface must be well polished, and be precleaned in 20% H_3PO_4 at 95 °C (205 °F) for uniform wettability. After precleaning, rinse in cold water and immediately immerse in etchant for 30 s.
11	2 g NaOH, 5 g NaF, 93 mL water	Immerse for 2 to 3 min.
12	50 mL Poulton's reagent (etchant 4 in Table 1), 25 mL HNO_3 (conc), 40 mL of solution of 3 g chromic acid per 10 mL of water	Put a few drops on as-rolled or as-extruded surface for 1 to 4 min, rinse, and swab to desmut. Examine on microscope with crossed polarizers to show grains. Repeat etching, if necessary. For some 5*xxx* alloys, increase amount of HNO_3 in solution to 50 mL
13	8 mL HNO_3 (conc), 2 mL HCl (conc), 45 mL water, 45 mL methanol	Immerse for 10 s
14	5 mL acetic acid (glacial), 1 mL HNO_3 (conc), 94 mL water	Immerse for 20 to 30 min.

Table 4 Applicability of etchants in Table 3 to microscopic examination of aluminum alloys

Alloy	Etchant	Evidence revealed
Examination for grain size and shape		
1*xxx*, 3*xxx*, 5*xxx*, 6*xxx* series; most casting alloys	5 or 12	Grain contrast when using crossed polarizers, with or without sensitive tint
2*xxx*, 7*xxx* series; Al-Cu or Al-Zn casting alloys	3A or 11	Grain contrast or grain-boundary lines
5*xxx* series alloys with more than 3% Mg	8 (3-5 min)	Precipitation in grain boundaries
Examination for cold working		
1*xxx*, 3*xxx*, 5*xxx*, 6*xxx* series alloys	5 or 12	Deformation bands or markings that cause streaked effect when using crossed polarizers
2*xxx*, 7*xxx* series alloys	3A or 11	Deformation bands or markings that accompany relatively great amounts of cold working
5*xxx* series alloys with more than 3% Mg	8 (3-5 min)	Precipitation in bands of slip
Examination for incomplete recrystallization		
1*xxx*, 3*xxx*, 5*xxx*, 6*xxx* series alloys	5 or 12	Even-toned, well-outlined grains that are recrystallized, otherwise streaked, or banded
2*xxx* series alloys, hot worked and heat treated	3A or 11	Unrecrystallized grains made up of multiple, very fine subgrains
6*xxx* series alloys, hot worked and heat treated	9	Unrecrystallized grains made up of multiple, very fine subgrains
7*xxx* series alloys, hot worked and heat treated	8 (3-5 min) or 14	Unrecrystallized grains made up of multiple, very fine subgrains

Examination for preferred orientation		
1*xxx*, 3*xxx*, 5*xxx*, 6*xxx* series alloys	5 or 12	Predominance of certain gray tones when crossed polarizers are used, lack of randomness
2*xxx* series alloys in T4 temper	3A or 11	Lack of randomness in grain contrast
Examination for overheating (partial melting)		
2*xxx* series alloys	8 (1 min)	Rosettes and grain-boundary eutectic
6*xxx* series alloys	2	Grain-boundary eutectic formations
7*xxx* alloys	3B	Rosettes and grain-boundary eutectic formations
Examination for general constituent size and distribution		
All wrought alloys and casting alloys	1, 8 (1 min) or any etchant that does not pit solid-solution matrix	Coarse insoluble particles and fine precipitate particles. Longer etching time exaggerates size of fine particles.
Examination for distinction between solution heat treated (T4) and artificially aged (T6) tempers		
2*xxx* series alloys	3A or 11	Loss of grain contrast, general darkening, in T6 compared with T4
6061	9	Clear outlining of grain boundaries in T6; faint outlining in T4
7075, recrystallized	4	More grain contrast, sharper grain-boundary outlining, in T4
Examination for over-aging or poor quenching of solution heat treated alloy		
2017 and 2024, in T4 temper	6	Faint dark precipitate at grain boundaries
Examination for cladding thickness		
Alclad 2014, 2024, 7075	3A or 11	Boundary between high grain contrast or outlining of alloy core and lighter-etching cladding
Brazing sheet	1 (swab) or 13	Boundary of high-silicon cladding alloy
Other clad alloys	1 (immerse), 2, 3A, 5, or 11	Any differences in structure that demarcate one layer from another
Examination for solid-solution coring or segregation, and diffusion effects		
3*xxx*, 5*xxx* series; Al-Mg casting alloys	10	Interference colors due to differences in thickness of tarnish films laid down on the surface
2*xxx* sereis alloys and others with more than 1% Cu	3A or 11	Brownish-colored films due to redeposition of copper

Technique for Copper and Copper Alloys

PREPARATION OF SPECIMENS of wrought and cast copper and copper alloys for macroexamination and microexamination is subject to the same general rules and recommendations as those that apply to preparation of specimens of other metals.

Technique for Macroexamination

Specimens for macroscopic examination are extracted from larger masses using common cutting techniques.

Surface preparation for macroetching usually can be obtained in two machining operations. In the first operation, a heavy cut is taken to remove the metal that was cold worked during sectioning; in the second operation, a light cut is taken using a V-shaped tool, or the specimen is ground to remove the remaining effects of cold work.

Etching. Deep etching removes the effects of cold work but produces a rough surface, and so it is common practice to deep etch the machined or rough-ground surface, regrind it lightly, and then give it a light etch. Selection of an etchant for a macrospecimen depends mainly on the alloy to be etched and the features to be examined. Frequently, the capabilities of two or more etchants overlap (or are the same), so that selection of a specific etchant is arbitrary. Table 5 gives compositions of the more commonly used macroetchants, along with etching procedures, purposes of the etchants or characteristics revealed, and alloys for which they are ordinarily used.

Table 5 Etchants for macroscopic examination of coppers and copper alloys

Procedure for use: immerse at room temperature, rinse in warm water, dry

Composition of etchant	Copper or copper alloy	Purpose, or characteristic revealed
50 mL HNO_3, 0.5 g $AgNO_3$, 50 mL water	All coppers and copper alloys	Produces a brilliant, deep etch
10 mL HNO_3, 90 mL water	Coppers and all brasses	Grains; cracks and other defects
50 mL HNO_3, 50 mL water(a)	Coppers, all brasses, aluminum bronze(b)	Same as above; reveals grain contrast
30 mL HCl, 10 mL $FeCl_3$, 120 mL water or methanol	Coppers and all brasses	Same as etchant above(c)
20 mL acetic acid, 10 mL 5% CrO_3, 5 mL 10% $FeCl_3$, 100 mL water(d)	All brasses	Produces a brilliant, deep etch
2 g $K_2Cr_2O_7$, 4 mL saturated solution of NaCl, 8 mL H_2SO_4, 100 mL water(e)	Coppers, high-Cu alloys, phosphor bronze	Grain boundaries, oxide inclusions
40 g CrO_3, 7.5 g NH_4Cl, 50 mL HNO_3, 8 mL H_2SO_4, 100 mL water	Silicon brass, silicon bronze	General macrostructure

(a) Solution should be agitated during etching, to prevent pitting of some alloys.

(b) Aluminum bronzes may form smut, which can be removed by brief immersion in concentration HNO_3.

(c) Excellent for grain contrast.

(d) Amount of water can be varied as desired.

(e) Immerse specimen for 15 to 30 min, then swab with fresh solution.

Technique for Microexamination

Specimens of copper and copper alloys for microscopic examination are extracted from larger masses by sawing, shearing, filing, hollow boring, or abrasive-wheel cutting.

Mounting. In general, the practice used for mounting copper and copper alloy specimens is the same as for mounting specimens of other metals.

Grinding. Wet grinding is preferred for all coppers and copper alloys. In the traditional approach, the practice is first to rough grind the specimen surface so as to remove metal that has been cold worked, then finish grind to obtain a suitable surface. Finish grinding is done on flat wheels using silicon carbide papers of progressively finer grit sizes, usually 240, 320, 400, and 600 mesh.

Rough Polishing. Most copper and copper alloys are relatively soft and thus require a polishing medium that provides maximum cutting action with minimum rubbing. Rough polishing should be done on diamond-impregnated nylon cloth. Duck, canvas, wool broadcloth, and cotton (listed in order of decreasing preference) are also used for polishing.

Although diamond paste is more expensive than other coarse abrasives, it is preferred by metallographers because it provides faster and more effective polishing. Diamond paste of 3 to 9 μm size is the preferred abrasive for rough polishing on any of the cloths mentioned above. A wheel speed of about 150 to 300 rpm is generally recommended.

Finish Polishing. Generally, napped cloths are preferred for finish polishing. Abrasive is usually 0.3 μm alpha alumina or 0.05 μm gamma alumina; both abrasives are used with water as a vehicle. Other abrasives that have proved satisfactory for finish polishing are magnesium oxide in distilled water and colloidal silica. A wheel speed of 150 to 300 rpm is recommended.

There are numerous opinions on how the specimen should be rotated during polishing. In hand polishing, the specimen generally is rotated in a direction opposite the wheel rotation while moving from edge to center. After polishing, the specimen is rinsed in water and dried with warm air. Automatic polishing (usually vibratory) has proved highly successful for polishing copper and its alloys. In automatic polishing, human variables are greatly minimized. Attack polishing (combined polishing and etching) with 1% ferric nitrate or with ammonium hydroxide-ammonium persulfate (Table 6) can be more safely done with automatic equipment than by hand.

Table 6 Etchants and procedures for microetching of coppers and copper alloys

<table>
<tr><th colspan="3">Etchant composition[a]</th><th>Procedure</th><th>Copper or copper alloy</th></tr>
<tr><td colspan="3">20 mL NH_4OH, 0 to 20 mL water, 8 to 20 mL H_2O_2 (3%)</td><td>Immersion or swabbing for 1 min. (H_2O_2 content varies with copper content of alloy to be etched; use fresh H_2O_2 for best results.)[b]</td><td>Coppers and copper alloys. Film on etched aluminum bronze can be removed with weak Grard's solution.</td></tr>
<tr><td colspan="3">1g $Fe(NO_3)_3$ 100 mL water</td><td>Add dropwise to the cloth during polishing with an abrasive, such as alumina.</td><td>Attack polishing of coppers and copper alloys</td></tr>
<tr><td colspan="3">25 mL NH_4OH, 25 mL water, 50 mL $(NH_4)_2S_2O_8$ (2.5%)</td><td>Add dropwise to the cloth during polishing with an abrasive, such as alumina.</td><td>Attack polishing of coppers and some copper alloys</td></tr>
<tr><td colspan="3">2 g $K_2Cr_2O_7$, 8 mL H_2SO_4, 4 mL NaCl (saturated solution), 100 mL water</td><td>Immersion. (NaCl replaceable by 1 drop HCl per 25 mL solution; add just before using.) Follow with $FeCl_3$ or other contrast etch.</td><td>Coppers; copper alloys of beryllium, manganese, and silicon; nickel silver; bronzes; chromium copper</td></tr>
<tr><td colspan="3">CrO_3 (saturated aqueous solution)</td><td>Immersion or swabbing</td><td>Coppers, brasses, bronzes, nickel silver</td></tr>
<tr><td colspan="3">50 mL CrO_3 (10 to 15%), 1 to 2 drops HCl</td><td>Immersion (add HCl at time of use)</td><td>Same as above. Color by electrolytic etching or with $FeCl_3$ etchants.</td></tr>
<tr><td colspan="3">10 g $(NH_4)_2S_2O_8$, 90 mL water</td><td>Immersion (use either cold or boiling)</td><td>Coppers, brasses, bronzes, nickel silver, aluminum bronze</td></tr>
<tr><td colspan="3">10% aqueous solution of copper ammonium chloride plus ammonium hydroxide to neutrality or alkalinity</td><td>Immersion. Wash specimen thoroughly.</td><td>Coppers, brasses, nickel silver; darkening large areas of beta in alpha-beta brass</td></tr>
<tr><td>FeCl, g</td><td>HCl, mL</td><td>Water, mL</td><td rowspan="7">Immersion or swabbing. Etch lightly or by successive light etches to required results</td><td rowspan="7">Coppers, brasses, bronzes, aluminum bronze; darkens beta in brass: gives contrast following dichromate and other etches</td></tr>
<tr><td>5</td><td>50</td><td>100</td></tr>
<tr><td>20</td><td>5</td><td>100[c]</td></tr>
<tr><td>25</td><td>25</td><td>100</td></tr>
<tr><td>1</td><td>20</td><td>100</td></tr>
<tr><td>8</td><td>25</td><td>100</td></tr>
<tr><td>5</td><td>10</td><td>100[d]</td></tr>
<tr><td colspan="3">5 g $FeCl_3$, 100 mL ethanol, 5 to 30 mL HCl</td><td>Immersion or swabbing for 1 s to several minutes.</td><td>Coppers and copper alloys</td></tr>
<tr><td colspan="3">Nitric acid (various concentrations)</td><td>Immersion or swabbing. $AgNO_3$ (0.15 to 0.3%) added to 1:1 solution gives a brilliant, deep etch.</td><td>Coppers and copper alloys</td></tr>
<tr><td colspan="3">Ammonium hydroxide (dilute solutions)</td><td>Add dropwise to the cloth during polishing with an abrasive</td><td>Attack polishing of brasses and bronzes</td></tr>
<tr><td colspan="3">50 mL HNO_3, 20 g CrO_3, 30 mL water</td><td>Immersion</td><td>Aluminum bronze, free-cutting brass. Film from polishing can be removed with 10% HF.</td></tr>
<tr><td colspan="3">5 mL HNO_3, 20 g CrO_3, 75 mL water</td><td>Immersion</td><td>Same as above</td></tr>
<tr><td colspan="3">50 mL cold saturated solution of sodium thiosulfate, 1 g potassium metabisulfite</td><td>Lightly pre-etch specimen with 10% aqueous ammonium persulfate. Immerse in solution until surface is colored. Gently agitate.</td><td>Tint etch for many copper and copper alloys. Produces brilliant colors. Colors beta more rapidly than alpha. Can be stored and used over.</td></tr>
<tr><td colspan="3">5 g ferric nitrate, 25 mL HCl, 70 mL water</td><td>Immersion solution for 10 to 30 s</td><td>Excellent general-purpose etchant for coppers and copper alloys. Good grain-boundary etchant.</td></tr>
<tr><td colspan="3">3 g ammonium persulfate, 1 mL ammonium hydroxide, 100 mL water</td><td>Swab for 5 to 20 s</td><td>Excellent etchant for coppers and copper alloys, particularly beryllium copper. Reveals grain boundaries in solution-annealed specimens.</td></tr>
</table>

(a) The use of concentrated etchants is intended unless otherwise specified.

(b) May be alternated with $FeCl_3$.

(c) Grard's No. 1 etchant. Plus 1 g CrO_2.

(d) Grard's No. 2 etchant. Plus 1 g $CuCl_2$ and 0.05 g $SnCl_2$.

Chemical Etching. Table 6 lists chemical etchants that are used for microetching copper and copper alloys, and it includes etching procedures and the alloys to which each etchant is commonly applied. The solution listed first in Table 6 is by far the most widely used etchant. It is probably the best for routine work and is applicable to many copper and copper alloys.

Technique for Lead and Lead Alloys

PREPARATION OF LEAD AND LEAD ALLOY SPECIMENS for metallographic examination presents problems that are not common to preparation of most other metals, because lead and lead alloys are so soft that they deform even under low pressure. Consequently, considerable surface flow or distortion can occur and abrasives can become embedded during grinding and polishing and, if not removed, can obscure the true structure of the specimen being examined. In the traditional method, preparation entails grinding with 400 grit SiC abrasive, rough polishing with 9 μm diamond paste on a napless cloth and 0.3 μm Al_2O_3 slurry on a medium-nap cloth, and final polishing with colloidal silica on a medium-nap cloth using light pressure until the surface is bright and scratch-free. In addition, because of the low melting points of lead and lead alloys, deformation of the specimen in metallographic preparation can be sufficient to cause heating and recrystallization. Therefore, in preparation of lead and lead alloy specimens, it is mandatory to employ a technique that will result in minimum surface distortion and heating. Use of a cold mounting procedure will enable the metallographer to avoid microstructural and crystallographic changes.

Etching

Table 7 gives compositions of the etchants most often used for macroetching and microetching of lead and lead alloy specimens. Etching procedures and specific uses for the various etchants are also included in Table 7. All but two of these etchants are used by immersing or swabbing the specimen; only etchants 9 and 10 are used electrolytically.

Table 7 Recommended etchants and procedures for macroscopic and microscopic examination of lead and lead alloys

Etchant No.	Composition (parts are by volume)	Procedure	Use
1	1 part acetic acid (glacial) 1 part nitric acid (conc) 4 parts glycerol	Use freshly prepared solution at 80 °C (175 °F); discard after use. For macroetching: etch several minutes, rinse in water. For microetching: etch several seconds. For best results, alternate etching with polishing.	Macroetching of lead; development of microstuctures and grain boundaries in lead, and in lead-calcium, lead-antimony, and lead-tin (low-Sn) alloys
2	100 parts acetic acid (glacial) 10 parts hydrogen peroxide (30%)	Etch for 10-30 min, depending on the depth of the disturbed layer. Dry and clean with concentrated nitric acid if required.	Microethcing of lead-antimony alloys containing up to 2% antimony
3	3 parts acetic acid (glacial) 1 part hydrogen peroxide (30%)	Etch by immersing specimen in solution for 6-15 s. Dry with alcohol.	Microetching of lead, lead-calcium alloys, and lead-antimony alloys containing more than 2% antimony. Also removes disturbed metal.
4	Solution A: 15 g ammonium molybdate 100 mL distilled water Solution B: 6 parts nitric acid (conc) 4 parts distilled water	Mix equal quantities of solutions A and B. Etch by alternately swabbing specimen and washing in running water.	Macroetching of lead. A very rapid etchant; well suited for removing thick layers of disturbed metal from specimens.
5	3 parts acetic acid (glacial) 4 parts nitric acid (conc) 16 parts distilled water	Use freshly prepared solution at 40 to 42 °C (104 to 108 °F). Immerse specimen for 4-30 min until disturbed layer is removed. Clean with cotton in running water.	Microetching of unalloyed lead, and lead-tin alloys containing up to 3% tin
6	2 parts acetic acid	Etch for 2-10 s by swabbing. Rinse specimen in	Macroetching of unalloyed lead, and of lead-

	(glacial) 2 parts nitric acid (conc) 2 parts hydrogen peroxide (30%) 5 parts distilled water	running water and dry with alcohol.	bismuth, lead-tellurium, and lead-nickel alloys
7	1 part nitric acid (conc) 1 part distilled water	Etch for 5-10 min by immersion. If thick layer of disturbed metal is to be removed, solution can be heated to boiling. Rinse in running water, rinse in alcohol, and dry.	Developing macrostructure of welds and laminations in lead products.
8	Solution A: 10% aqueous solution of ammonium persulfate Solution B: 30% aqueous solution of tartaric acid	Mix 5 mL of solution A with 2 mL of solution B. Swab specimen for 5-10 s. Rinse in running water.	Microetching to distinguish cuboidal SbSn phase from Sb-rich phases in Pb-Sb-Sn alloys, such as bearing alloys or type metals. Solution A blackens SbSn phase; solution B etches Sb-rich phases.
9	6 parts perchloric acid (70%) 4 parts water	Immerse specimen (cathode) in electrolyte; anode is platinum spiral. Etch 45-90 s at 6 V, 4 A, from a rectifier.	Electrolytic etching of lead-antimony alloys containing more than 2% antimony
10	1 part hydrochloric acid (conc) 9 parts water	Same as for etchant 9	Same as for etchant 9
11	10 g ammonium molybdate 10 g citric acid 100 mL water	Etch for 15-30 s by immersion, rinse in warm water and alcohol and blow dry.	Delicate etch for lead and lead alloys. Ideal for revealing phases for high-magnification examination, microstructures, and grain boundaries in lead and in lead-calcium, lead-antimony, and lead-tin (low-Sn) alloys

Primarily because lead and lead alloys smear so easily, etch-polishing alternated with examination under the microscope was traditionally recommended. Sometimes, several cycles of polishing, etching, and examination were considered necessary; thus, a great deal of skill and patience was required. In addition to smearing, lead-antimony alloys are susceptible to tarnishing (or blackening) during etching. One or two light turns on the final polishing wheel, followed by immersion of the specimen in water, rinsing in ethanol or methanol, and drying in warm air, is often sufficient to remove this tarnish and reveal the true structure. Another technique involves use of a camel hair brush and liquid hand soap to remove the black etching product, followed by rinsing in a strong stream of running water and drying with alcohol and a warm air blast. Discoloration resulting from overetching or oxidation, or both, can sometimes be removed by lightly swabbing the specimen with EDTA (a solution of ethylenediamine tetraacetic acid disodium salt). Final vibratory polishing with colloidal silica eliminates most of these problems and a sensitive etch, such as number 11 from Table 7, can be used without need of multiple etch-polish cycles.

Lead and lead alloys begin to oxidize immediately after metallographic preparation and should be examined as soon as possible. Although EDTA sometimes removes the discoloration resulting from oxidation, the best solution is thorough drying of the specimen after etching. EDTA will not solve the problem of overetching.

Technique for Magnesium Alloys

SPECIMENS OF MAGNESIUM ALLOYS for metallographic examination should be chosen with care so as to be representative. For example, both longitudinal and transverse specimens of sheet should be examined, edge and center sections of large ingots should be considered, and the mouth of a casting crack should be studied as the point of origin of the crack.

Specimen Preparation

Specimens are removed from the metal mass by band sawing, hacksawing or abrasive cutting. Care should be exercised to prevent cold working of the metal, because cold working can alter the microstructure and complicate interpretation of constituents.

Specimens that have been severely cold worked by rough sawing, squeezing in a vise, or heavy stamping are likely to be mechanically twinned close to the worked surface. The cold worked surface can be removed by extending the time of each grinding and polishing operation up to twice the time required for removing scratches from the preceding stage. Removal of metal to a depth of approximately 1 mm (0.040 in.) during preparation of the specimen is recommended. The safest procedure is to minimize deformation in sectioning so that twinning is avoided or at least minimized.

Grinding. Wet grinding can be done on abrasive belts, rotating disks, or on abrasive papers by hand.

Mechanical polishing is traditionally done in two stages: rough and finish. Rough polishing removes the major part of the disturbed metal remaining after the final grinding step. Finish polishing removes the superficial scratches that remain after rough polishing.

Wheels used for both polishing stages are covered with medium-nap cloths. A suspension of 600 grit aluminum oxide powder in distilled water (35 g of aluminum oxide per 500 mL of water) is used on the wheel for rough polishing; for best results, the cloth is maintained just moist enough to prevent seizure of the specimen. The specimen is rotated counter to wheel direction. Polishing time should be twice as long as is needed to remove the scratches from the final grinding operation. A moderate amount of pressure should be used to minimize relief polishing caused by the difference in rate of stock removal between the harder and softer microconstituents.

For finish polishing, a suspension of alpha alumina in distilled water (10 g of alumina per 500 mL of water) is used on the wheel. Sometimes, to facilitate polishing, 15 mL of filtered or other soft soap is added to the abrasive solution.

Macroetching. The macroetchant most often used for showing discontinuities in castings and flow lines in forgings is an aqueous solution containing 5 to 20% acetic acid. The etchant is swabbed on the prepared surface for 10 s to 3 min and then washed away in running water. To show the grain structure of impact extruded or forged parts that have a homogeneous recrystallized structure and a minimum of alloy gradients, and for castings, one of the acetic-picral etchants listed in Table 8 as etchants 6, 7, or 8 should be used. The part is immersed in the etchant for 10 s to 1 min, transferred to a pan of ethanol to rinse the etched surface uniformly, rinsed in flowing ethanol, and then dried in a blast of air.

Table 8 Selected etchants for macroscopic and microscopic examination of magnesium alloys

Etchant No.	Composition	Etching procedure	Characteristics and use
1	*Nital:* 1 to 5 mL HNO_3 (conc), 100 mL ethanol (95%) or methanol (95%)	Swab or immerse specimen for a few seconds to 1 min. Wash in water then alcohol and dry.	Shows general structure.
2	*Glycol:* 1 mL HNO_3 (conc), 24 mL water, 75 mL ethylene glycol	Immerse specimen face up and swab with cotton for 3-5 s for as-cast or aged metal, and up to 1 min for heat treated metal. Wash in water, then alcohol and dry.	Shows general structure. Reveals constituents in Mg-rare earth and Mg-Th alloys.
3	*Acetic glycol:* 20 mL acetic acid, 1 mL HNO_3 (conc), 60 mL ethylene glycol, 20 mL water	Immerse specimen face up with gentle agitation for 1-3 s for as-cast or aged metal, and for 10 s for heat treated metal. Wash in water, then alcohol and dry.	Shows general structure and grain boundaries in heat treated castings. Shows grain boundaries in Mg-rare earth and Mg-Th alloys.
4	10 mL HF (48%), 90 mL water	Immerse specimen face up for 1-2 s. Wash in water, then alcohol and dry.	Darkens $Mg_{17}Al_{12}$ phase and leaves $Mg_{32}(Al,Zn)_{49}$ phase unetched and white.
5	*Phospho-picral:* 0.7 mL H_3PO_4, 4 to 6 g picric acid, 100 mL ethanol (95%)	Immerse specimen face up for about 10-20 s, or until polished surface is darkened. Wash in alcohol and dry.	For estimating the amount of massive phase. Stains matrix and leaves phase white. Staining improves as magnesium-ion content increases with use.
6	*Acetic-picral:* 5 mL acetic acid, 6 g picric acid, 10 mL water, 100 mL ethanol (95%)	Immerse specimen face up with gentle agitation until face turns brown. Wash in a stream of alcohol and dry with a blast of air.	A universal etchant. Defines grain boundaries in most alloys and tempers by etch rate and color of stain. Reveals cold work and twinning readily.
7	*Acetic-picral:* 20 mL acetic acid, 3 g picric acid, 20 mL water, 50 mL ethanol (95%)	Same as for etchant 6, above, but etch for at least 15 s to develop a heavy film.	Orientation of crackled film is parallel to trace of basil plane. Film crackles in high-alloy areas. Distinguishes between fusion voids surrounded by normal level of alloy and microshrinkage with low alloy content.
8	*Acetic-picral:* 10 mL acetic	Same as for etchant 6, above	Reveals grain boundaries more readily than etchant 6,

	acid, 4.2 g picric acid, 10 mL water, 70 mL ethanol (95%)		above, especially in dilute alloys.
9	0.6 g picric acid, 10 mL ethanol (95%), 90 mL water	Immerse specimen face up for 15-30 s. Wash in alcohol and dry.	Use after HF etchant to darken matrix to give better contrast between matrix and white ternary phase.
10	2 mL HF (48%), 2 mL HNO_3 (conc), 96 mL water	Immerse specimen face up with gentle agitation. Do not swab.	Grain structure and coring in Mg-Zn-Zr alloys.

Microexamination

The etchants used and etching times depend on the physical condition and temper of the specimen. Time may vary from 5 to 10 s for a specimen of an alloy in the as-cast or aged condition to 30 s for one in the solution heat treated condition. Etchants used for specimens of magnesium alloys are listed in Table 8, along with their compositions, etching procedures, characteristics, and uses. For sand, permanent mold, and die cast alloys in the as-cast condition and for virtually all of the alloys in the aged condition, the glycol etchant is used; it is especially good for the magnesium-rare earth alloys and magnesium-thorium alloys. Acetic-picral etchants are used to selectively stain the grains, especially for viewing with sensitive-tint or polarized light.

Technique for Nickel and Nickel Alloys

PREPARATION OF METALLOGRAPHIC SPECIMENS is divided into two classes of nickel alloys: alloys containing 96% or more nickel (Nickel 200, Nickel 270, and Duranickel 301) and nickel-copper alloys (Monel 400, Monel R-405, and Monel K-500). Techniques for nickel-base magnetic alloys and wrought heat-resisting alloys are discussed elsewhere in this article.

The procedures and materials used in sectioning, mounting, grinding, and polishing of specimens are essentially the same for all of the nickel alloys. In preparing specimens for metallographic examination, it is important to prevent cold working of the surface.

Preparation for Macroscopic Examination

The preparation steps and macroetching procedures for these alloys are essentially the same as for steels. Resolution of detail is improved as the quality of the ground surface increases. Macroetching of nickel alloys is performed by immersion or swabbing using a cold solution of nitric acid and acetic acid (equal parts by volume) for times less than about 30 s. For nickel-copper alloys, fresh concentrated nitric acid is preferred. Times up to 5 min may be needed. Stale nitric acid may produce staining. Shorter times are recommended to observe sulfur embrittlement in Monel welds whereas longer times reveal macrostructural features.

Preparation for Microscopic Examination

Sectioning, mounting, grinding, and polishing steps for nickel and nickel-copper alloys are quite similar to those for austenitic stainless steels. The chief danger is introduction of cold work to the structure. As with austenitic stainless steels, removal of fine scratches requires careful final polishing.

SiC papers are recommended for grinding, in the traditional manner, using the sequence 120, 240, 320, 400, and 600 grit with water cooling. Rough polishing with 6 μm diamond paste on a low- or medium-nap cloth followed by 1 μm diamond on the same type of cloth will produce excellent results. Final polishing with a 0.05 μm alumina slurry or colloidal silica on a medium-nap cloth produces excellent results. Vibratory polishing with either of these abrasives may be required to obtain optimum results.

An alternative procedure is to electropolish specimens after mechanical polishing to remove fine scratches and deformation. Recommended electrolytes and current densities for electropolishing these alloys are given in Table 9. A platinum cathode should be used, and the electrolyte should be water cooled and continuously stirred.

Table 9 Electrolytes and current densities for electropolishing of nickel and nickel-copper alloys

Composition of electrolyte	Applicable alloys	Current density	
		A/cm^2	**$A/in.^2$**
37 mL H_3PO_4 (conc), 56 mL glycerol, 7 mL water	Nickel 200	1.4-1.6	9-10
	Nickel 270	1.6-1.9	10-12
	Duranickel 301	1.2-1.6	8-10
	Monel 400	0.9-1.1	6-7
33 mL HNO_3 (conc), 66 mL methanol	Monel 400, R-405, K-500	1.6-2.3	10-15

Etching. The solutions and conditions for etching the various nickel alloys for microscopic examination are described in Table 10. The acids used should be concentrated; when water is indicated, use distilled water only.

Table 10 Etchants for microscopic examination of nickel and nickel-copper alloys for grain boundaries and general structure

Composition of etchant	Conditions for use
Etchants for Nickel 200 and 270; Duranickel 301; and Monel 400, R-405, and K-500	
1 part 10% aqueous solution of sodium cyanide, 1 part 10% aqueous solution of ammonium persulfate; mix solutions when ready to use	Immerse or swab specimen for 5-90 s (*Caution:* use fume hood; solutions release toxic fumes when mixed.)
1 part nitric acid (conc), 1 part acetic acid (glacial). Use fresh solution.	For revealing grain boundaries. Immerse or swab specimen for 5-20 s.
Alternative etchant for Monel K-500	
Glyceregia: 10 mL nitric acid (conc), 20 mL hydrochloric acid (conc), 30-40 mL glycerol	Etch by immersing or swabbing the specimen for 30 s to 5 min.

Technique for Wrought Heat-Resisting Alloys

WROUGHT HEAT-RESISTING ALLOYS exist in three major classes: iron-nickel-chromium alloys, nickel-base alloys, and cobalt-base alloys.

Although the three classes of alloys differ significantly in composition, microstructure, and elevated-temperature properties, the technique and equipment used for preparation of metallographic specimens are essentially the same for all three classes. Further, the technique used for these wrought alloys is basically the same for their cast counterparts and similar to those used for other metals.

Metallographic Technique for Nonferrous Metals and Special-Purpose Alloys

Edited by George F. Vander Voort, Buehler Ltd.

Specimens for Light Microscopy

Sectioning and Grinding. The initial preparation stages of sectioning and mounting (if required) are virtually identical to those employed for steels. Likewise, traditional coarse and fine grinding procedures are also similar, using water-cooled SiC papers of 120, 240, 320, 400, and 600 grit. If grinding is done manually, the direction of grinding must be rotated 45 to 90° between each step.

Polishing. Rough polishing is generally performed with 3, 6, or 9 μm diamond paste on a napless or low-nap cloth, such as nylon or silk, to minimize relief at the hard constituents. This step may be followed by a similar step using 0.5 or 1 μm diamond paste on a napless or low-nap cloth. If these steps are done manually, the specimen should be rotated against the cloth in the direction opposite to wheel rotation until scratches from the previous step are removed.

Final polishing can be performed using a variety of abrasives and cloths (napless to medium nap). If two diamond polishing steps were used, final polishing may be conducted using abrasives such as 0.05 μm alumina (water slurry) or colloidal silica. If only one diamond polishing step (e.g., 6 μm diamond) was used, two different alumina abrasive steps, such as 0.3 and 0.05 μm, may be desired. Polishing pressure should be light to moderate depending on the alloy being polished.

In recent years, considerable use has been made of automatic polishing devices for the grinding and polishing steps. The more fully automated devices permit precise duplication of the polishing cycle, which improves reproducibility of polishing results and generally produces better control of relief than can be achieved with manual polishing. Vibratory polishing has often been used for final polishing, with both fine diamond and fine abrasive slurries. Although polishing times are substantially longer, excellent results can be obtained. Typically, times up to about 30 min are required with each abrasive used in this manner.

Etching. Procedures for specific wrought heat-resisting alloys of the three major classes are listed in Tables 11, 12, and 13. Compositions of the etchants used are given in Table 14.

Table 11 Microetching procedures for wrought iron-nickel-chromium heat-resisting alloys

Etchant No.(a)	Etching method	Etching time, s	Cell voltage	Purpose, or characteristics revealed
Alloy A-286				
1	Swab	3-20	. . .	General structure
2	Swab	5-60	. . .	General structure; may stain or pit
3	Immerse	10-60	. . .	General structure
Incoloy 800				
4	Electrolytic	15-30	5-10	General structure; grain boundaries
5	Electrolytic	10-20	5-10	Grain boundaries; carbide particles
6	Electrolytic	10-15	20	Carbide particles
7	Swab	15-30	. . .	Grain boundaries(b); carbide. No staining.
8	Electrolytic	10-30	10	Preferential attack at grain boundaries
Incoloy 825				
4	Electrolytic	15-30	5-10	General structure; grain boundaries
5	Electrolytic	10-20	5-10	Grain boundaries; carbide particles
7	Swab	15-30	. . .	Grain boundaries; carbide. No staining.
9	Swab or immerse	(c)	. . .	General structure
RA 330				
8	Electrolytic	5-10	5	For etch pitting
10	Electrolytic	2-10	3	General structure; precipitates

(a) See Table 14 for compositions of etchants.

(b) Grain boundaries are faint if free of carbide particles.

(c) Etching time varies from a few seconds to 12 min.

Table 12 Microetching procedures for wrought nickel-base heat-resisting alloys

Etchant No.(a)	Etching method	Etching time, s	Cell voltage	Purpose, or characteristics revealed
Hastelloy C				
11	Electrolytic	2-10	3	General structure
Hastelloy W				
12	Immerse	. . .	. . .	General structure
Hastelloy X				
13	Electrolytic	2-10	6	General structure. Remove stains with HNO_3.
Inconel 600 and 601				
4	Electrolytic	15-20	5-10	General structure. No pitting.
5	Electrolytic	15-20	5-10	General structure; grain boundaries; carbide
6	Electrolytic	15-20	5-10	General structure; excellent for revealing carbide particles
7	Swab or immerse	(b)	. . .	Grain-boundary contrast fair; carbide

14	Immerse	(c)(d)	. . .	General structure; carbide particles
Inconel 625				
8	Electrolytic	1-2	50	Grain boundary films. Results vary with thermal history of specimen.
15	Electrolytic	10-20	5-10	Grain boundaries. No staining. Results vary with thermal history of specimen.
16	Electrolytic	15-20	5-10	General structure; grain boundaries
17	Electrolytic	15-20	5-10	General structure
18	Electrolytic	8-20	2-10	Outlines phases. May cause pitting. Poor results on cold worked metal.
Inconel 706 and Alloy 718				
8	Electrolytic	1-2	50	Grain-boundary films. Shows grain boundaries in relief.
15	Electrolytic	10-20	5-10	Good for general structure and phase outline; grain boundaries
16	Electrolytic	15-20	5-10	Good for general structure, phase outline, and matrix segregation for most heat treated conditions; grain boundaries
17	Electrolytic	15-20	5-10	General structure; precipitate phases in fully heat treated material
19	Swab or immerse	(b)	. . .	General structure; microsegregation
20	Immerse	(e)	. . .	Carbide particles. Chromium carbide particles darken faster than nitrides and Laves phase.
Inconel X-750				
4	Electrolytic	15-20	5-10	General structure. No pitting.
5	Electrolytic	15-20	5-10	Grain boundaries; carbide. No pitting.
15	Electrolytic	10-20	5-10	Good for revealing grain boundaries and carbide particles
21	Swab	2-10	. . .	Excellent for showing details of overaged gamma prime
22	Swab	5-60	. . .	General structure; microsegregation
U-700				
23	Swab or immerse	10-20	. . .	Good for contrast(f)
24	Swab or immerse	(c)	. . .	General structure; grain boundaries. No staining.
28	Electrolytic	5-20	5-10	General structure; grain boundaries
Waspaloy				
1	Swab	3-20	. . .	General structure
24	Swab or immerse	(c)	. . .	General structure. No staining.
25	Swab or immerse	5-30	. . .	General structure

(a) See Table 14 for compositions of etchants.

(b) $\frac{1}{2}$-5 min.

(c) 1-5 min.

(d) Heat specimen to reduce etching time.

(e) 5-10 min.

(f) Use well-prepared specimen

Table 13 Microetching procedures for wrought cobalt-base heat-resisting alloys

Etchant No.(a)	Etching method	Etching time, s	Purpose
Haynes 25, Haynes 188			
26	Electrolytic, 6 V	2-5	(b)
Stellite 6B			
26	Electrolytic, 6 V	2-5	(b)
27:			
Stage 1	Electrolytic, 6 V	2-5	(b)
Stage 2	Immersion	5-10	(c)

(a) See Table 14 for compositions of etchants.

(b) General structure.

(c) Carbide particles

Table 14 Etchants for microscopic examination of wrought heat-resisting alloys

See Tables 11, 12, and 13 for applicability to specific alloys.

Etchant No. and name	Composition(a)	Remarks on preparation and use
1 HCl, HNO_3, acetic acid	15 mL HCl, 10 mL HNO_3, 10 mL acetic acid	. . .
2 Chrome regia	2 g CrO_3, 20 mL HCl, 80 mL water	CrO_3 may be increased, but staining may result.
3 Ferric chloride-hydrochloric	5 g $FeCl_3$, 15 mL HCl, 100 mL methanol	. . .
4 Nital	5 mL HNO_3, 95 mL methanol	Use colorless acid and absolute methanol.
5 Oxalic acid	10 g oxalic acid, 100 mL water	Can be stored.
6 Phosphoric acid	80 mL H_3PO_4, 20 mL water	Change to a 1:1 solution for specific results.
7 Glyceregia	10 mL HNO_3, 20 mL HCl, 40 mL glycerol	Must be freshly prepared.
8 Hydrochloric-methanol	10 mL HCl, 90 mL methanol	Water can be substituted for methanol to show segregation.
9 Vilella's reagent	5 mL HCl, 1 g picric acid, 100 mL methanol	A few drops of 3% H_2O_2 will speed etching reaction.
10 HCl-H_2O	5 mL HCl, 95 mL water	. . .
11 Chromic acid	2-10 g CrO_3, 100 mL water	. . .
12 Hydrochloric-chromic	80 mL HCl, 20 mL 50% chromic acid	Use fresh solution.
13 Oxalic acid	10 g oxalic acid, 90 mL water	. . .
14 Nitric-hydrofluoric	20 mL HNO_3, 3 mL HF	Use colorless acids. Remove thoroughly by water rinse.
15 Chromic-acetic	25 g CrO_3, 7 mL water, 130 mL acetic acid	Can be stored for up to one month.
16 Chromic acid	5 g CrO_3, 100 mL water	. . .
17 47-41-12	47 mL H_2SO_4, 41 mL HNO_3, 12 mL H_3PO_4	Add H_2SO_4 last, and slowly. Produces noxious fumes and is highly corrosive. When correctly etched, the specimen surface is colored brown.
18 Hydrochloric-acetic	10 mL acetic acid, 3 drops HCl, 90 mL water	. . .
19 Inverted glyceregia	50 mL HCl, 10 mL glycerol, 10 mL HNO_3	. . .
20 Murakami's reagent	10 g KOH or NaOH, 10 g $K_3Fe(CN)_6$, 100 mL water	Dissolve KOH (or NaOH) and $K_3Fe(CN)_6$ in boiling water; etch specimen in boiling solution. Prepare fresh for use.
21 Nitric-hydrofluoric	50 mL HNO_3, 50 drops HF	Use colorless acids.
22 Hydrochloric-hydrofluoric-nitric	80 mL HCl, 13 mL HF, 7 mL HNO_3	. . .
23 Marble's reagent	4 g $CuSO_4{\cdot}5H_2O$, 20 mL HCl, 20 mL water	Dissolve $CuSO_4$ in water and add HCl.
24 Kalling's reagent	2 g $CuCl_2$, 40 mL HCl, 80 mL methanol	Can be stored.
25 92-5-3	92 mL HCl, 5 mL H_2SO_4, 3 mL HNO_3	Must be freshly prepared.
26 Hydrochloric-hydrogen peroxide	97 mL HCl, 3 mL 3% H_2O_2	Must be freshly prepared.
27 Grosbeck's reagent (two-stage)	Stage 1:2 to 10% CrO_3 in water; stage 2: equal parts 20% $KMnO_3$, 8% NaOH	Mix second stage immediately before use.
28 HCl-ethanol-H_2O_2	35 mL HCl, 65 mL ethanol (95%), 7 drops H_2O_2 (30%)	Must be freshly prepared.

(a) Use concentrated acids, unless indicated otherwise. Use distilled water to avoid staining.

Technique for Magnetic Alloys

METALLOGRAPHIC TECHNIQUE differs widely for the several groups of magnetic materials that include silicon steels (also called electrical steels), iron-nickel alloys, iron-cobalt alloys, ferrites and garnets, and a variety of metals used for permanent magnets.

Silicon Steels

Techniques for cutting, mounting, grinding, and polishing are generally the same for specimens of silicon steels as for specimens of other low-carbon sheet steels.

Etching. For some purposes, such as revealing precipitated iron carbide in high-silicon steels, specimens are examined in the as-polished condition. Nital (2 to 10% nitric acid in ethanol) is used extensively for etching. Picral (4% picric acid in ethanol) is sometimes used instead of nital, especially for revealing grain-boundary carbides.

Grain Orientation. Crystallographic texture is often of particular interest in metallographic studies of silicon (electrical) steels. Pitting etchants, which selectively attack certain crystallographic planes, often are used to determine orientation with the aid of an optical goniometer. Results are not always consistent; details of preparation, including methods of rinsing and drying and other steps in the procedure, often must be determined individually for best results, and variations of the etchant are sometimes necessary. Pitting etchants that have been used successfully are listed in Table 15. Special techniques for observing magnetic domains include use of Bitter patterns, use of the magneto-optical Kerr effect, and the Lorenz technique.

Table 15 Pitting etchants for determination of grain orientation in silicon steels by light microscopy

Etchant	Composition (parts are by volume)	Conditions for use	Purpose
1	1 part HF, 1 part HNO_3, 4 parts water	Immerse for 10 s	Expose {100} crystallographic faces in (110)[001] (cube-on-edge) oriented 3.25% Si steel.
2	2 parts HF, 1 part HNO_3, 3 parts methanol, 4 parts glycerol	Swab for 1 min.	Same as for etchant 1.
3	A: 6 mL H_2O_2 (30%), 0.1 mL HCl, 100 mL water B: 40 mL $FeCl_3 \cdot 6H_2O_2$ 40 mL ethanol, 20 mL water	Immerse in A for 10 s, rinse and dry: then immerse in B for 3 s, rinse and dry.	Develops etch pits in (110)[001] (cube-on-edge) oriented 3.25% silicon steel.
4	100 g ferric sulfate, 100 mL H_2SO_4, 1000 mL water	Immerse for 15 s in solution heated to 80 to 90 °C (175 to 195 °F)	Develops etch pits in (100)[001] (cube-on-face) oriented 3.25% silicon steel.
5	A: 5 mL HF, 95 mL methanol B: 100 mL H_2O_2 (3%), 100 mL water, 2 drops HCl C: 5 mL HCl, 95 mL methanol	Polish, etch heavily in nital. Repolish, etch in nital to reveal grain boundaries. Immerse 10 s in A, rinse, dry; 2 s in B, rinse, dry; 30 s in C, rinse, dry	Exposes {100} crystallographic faces in primary recrystallized 3.25% silicon steel and nonoriented silicon steels.
6	600 g $FeCl_3$, 10 g ammonium bisulfate, 600 mL HCl, 150 mL HNO_3, 1650 mL water	Immerse for 1 min in solution heated to 50 to 60 °C (120 to 140 °F).	Exposes {111} crystallographic faces in secondary recrystallized 50Ni-50Fe.

Metallographic Technique for Nonferrous Metals and Special-Purpose Alloys

Edited by George F. Vander Voort, Buehler Ltd.

Iron-Nickel and Iron-Cobalt Alloys

Techniques used for preparing metallographic specimens of iron-nickel and iron-cobalt ferro-magnetic alloys generally are similar to those used for preparing specimens of other soft metals.

Macroetching. Macroexaminations of iron-nickel alloys frequently are made on specimens that have been subjected to thermal etching. In thermal etching, a polished specimen is placed in a furnace, usually with a charge of material for annealing, and is heated and cooled with the charge; annealing temperature is usually 1175 °C (2150 °F).

Mounting. If the grain size is to be determined on strip specimen surfaces, electropolishing and electroetching is often performed as it is simple, fast, and adequate. If the cross section is to be examined for surface conditions, inclusions, and so forth, then mounting is required. All of the usual aspects of mounting apply to these alloys.

Mechanical grinding and polishing of iron-nickel and iron-cobalt alloys are basically the same as for strip or sheet steel specimens. Traditional practice is to wet grind on a series of silicon carbide papers ending with 600 grit silicon carbide. Wet grinding minimizes embedding of abrasive particles in the soft-metal specimen. Rough polishing is done with 3 μm diamond on a napless cloth-covered wheel. Final polishing is preferably done with gamma alumina on a napped cloth.

Electropolishing is sometimes used for iron-nickel and iron-cobalt alloys. Common practice is to mechanically finish the specimen through 600 grit silicon carbide and then to electropolish. Two widely used electrolytes and typical electropolishing conditions are given in Table 16.

Table 16 Electrolytes and conditions for electropolishing of iron-nickel and iron-cobalt magnetic alloys

Alloy	Electrolyte	Conditions for use
Fe-Ni only	135 mL acetic acid (glacial), 25 g CrO_3, 7 mL water	80 V, 0.8 to 1.6 A/cm^2, 5-30 s at 7 °C (45 °F) max
Fe-Ni or Fe-Co	100 mL acetic acid (glacial), 10 mL perchloric acid	45 V, 0.2 A/cm^2, 3-4 min at 24 °C (75 °F)

Microetching. Table 17 lists several etchants that may be used for iron-nickel or iron-cobalt alloys. As shown in Table 18, some of the etchants in Table 17 are suitable for both groups of alloys; selection of etchant is often arbitrary. The first etchant listed in Table 17 (HCl), $CuCl_2$, $FeCl_3$, HNO_3, methanol, and water) is most often used. Some metallographers prefer to obtain an electrolytic etch by reducing the current following electropolishing with one of the two solutions for which compositions are given in Table 16. The pros and cons of electrolytic etching for iron-nickel and iron-cobalt alloys are much the same as for other metals. Chemical etching is preferred in most laboratories.

Table 17 Etchants for microscopic examination of iron-nickel and iron-cobalt magnetic alloys

See Table 18 for applicability

Etchant	Composition	Conditions for use[(a)]
Chemical etching		
1	100 mL HCl, 2 g $CuCl_2$, 7 g $FeCl_3$, 5 mL HNO_3, 200 mL methanol, 100 mL water	Immerse or swab for 10-15 s
2[(b)]	15 mL HCl, 5 g $FeCl_3$ (anhydrous), 60 mL ethanol	Immerse for 5-10 s
3	3 mL HCl, 1 mL HNO_3 saturated with $CuCl_3$	Swab for 2-3 s
4	15 mL HCl, 5 mL HNO_3, 10 mL glycerol	Swab for 10-15 s
5	Ammonium persulfate (saturated aqueous solution)	Immerse 20-30 s
6	2 to 10% nital (HNO_3 in ethanol or methanol)	Immerse for 5-10 s
7	50 mL HCl, 10 g $CuSO_4$, 50 mL water (Marble's reagent)	Immerse or swab for 5 s
Electrolytic etching		
8	5 to 10 mL HCl, 100 mL water	2-5 s at 250-500 mA/cm^2
9	2 g CrO_3, 100 mL water	2-5 s at 100-200 mA/cm^2
10	3% sulfuric acid	5-10 s

(a) All etchants are used at room temperature.

(b) Recommended for electron metallography.

Table 18 Etchants in Table 17 recommended for microscopic examination of iron-nickel and iron-cobalt magnetic alloys

Etchant	Characteristic revealed
Iron-nickel alloys	
1, 2, 3, 4, 5[(a)], 6	Grain size, structure
3[(b)], 7	Grain size
Iron-cobalt alloys	
1, 5, 6, 8, 9, 10	Grain size, structure

(a) For etching 50Fe-50Ni.

(b) For etching high-nickel alloys

Ferrites and Garnets

Because ferrites and garnets are electrical insulators, they cannot be electropolished or etched electrolytically. In addition, these materials are chemically inert and thus are not readily attacked by most etchants.

Preparation of specimens up to the point of etching is essentially the same as for metals. Magnetically soft and magnetically hard ferrites, including nickel and barium ferrites, are very often examined in the as-polished condition. This technique reveals voids and second phases. Grain size can be estimated from fractographs of broken surfaces (ferrites are brittle and fracture along grain boundaries) and by etching polished surfaces with strong reagents that results in attack on grain boundaries. Most etchants for nickel ferrites contain hydrofluoric acid, combined with nitric, sulfuric, or orthophosphoric acid, and are usually heated to 60 to 90 °C (140 to 195 °F). Etching time may range from a few seconds to 30 min.

Alnico Permanent Magnet Alloys

All Alnico alloys are hard (40 to 60 HRC) and brittle, so that specimens must be extracted by breaking or abrasive-wheel cutting, or both. When abrasive cutoff wheels are used, extreme care is needed to avoid cracking and burning of specimens; slow feeds and an adequate flow of coolant must be used. Best practice is to remove at least 1.6 mm ($\frac{1}{16}$ in.) from the cut face or to avoid using the cut face for examination. Because of the high hardness, grinding and polishing are difficult and slow; consequently, it is advisable to use relatively small specimens (polished face no greater than 160 mm^2, or $\frac{1}{4}$ in.^{2}).

Mounting prior to grinding and polishing is preferred for small specimens, although it is not essential for large specimens. Phenolic is most often used as the mounting material, but other materials may be used.

Grinding and Polishing. Grinding is traditionally performed using silicon carbide of progressively finer grit sizes through 600 grit. Rougher grinding may be done dry, but preferred practice is to use kerosene or light spindle oil for grinding with abrasive finer than 400 grit.

A polishing procedure satisfactory for routine examination of Alnico alloys consists of wet polishing the specimen (previously ground to the finish obtained with 600 grit abrasive) on a conventional rotating wheel with a napped cloth and 6 μm diamond abrasive. Final polishing may employ 0.05 μm size levigated alumina or chromic oxide of 0.5 μm size on a medium-nap cloth.

Etching. Specimens of Alnico alloys sometimes are examined without etching, principally for voids, such as porosity and microshrinkage. Also, unetched specimens are sometimes used for electron microscopy. Alnico alloys resist attack by many chemicals, and thus a relatively strong etchant is required. Marble's reagent is often used. Procedures for other permanent magnet materials, such as Cunife and rare-earth-cobalt alloys, may resemble those discussed previously. In some instances, etch-polishing or electrolytic techniques are necessary.

Technique for Tin and Tin Alloys

TIN AND TIN ALLOYS are extremely soft and have low recrystallization temperatures. Thus, preparation of tin and tin alloy specimens for metallographic examination presents special problems that are not often encountered in preparing specimens of other metals. However, many of the steps in preparation are similar or identical to those for other metals.

Mounting

Mounting of tin and tin alloy specimens should be done at room temperature, because elevated temperatures can cause structural changes, such as precipitation of a second phase from the supersaturated solid solution. Compression mounting compounds are therefore unsuitable.

Grinding and Polishing

Distortion of the surface layers of tin and tin alloys may cause recrystallization, which will mask the true structure. For tin alloys in a metastable state, distortion of the surface regions as a result of working may cause structural changes, such as precipitation from a supersaturated solid solution.

To avoid working of the surface regions, extreme care must be taken during turning, filing, sectioning, grinding, and polishing, because of the susceptibility to distortion during those operations.

Grinding. The specimen is wet ground on silicon carbide papers of progressively finer grit sizes (180, 240, 320, 400, and 600 grit). The papers are kept wet by a continuous stream of lubricant, usually water, that washes away the particles of metal as they are cut from the surface of the specimen. This removal prevents clogging of the papers, which would lead to surface flowing of the metal instead of cutting. For alloys containing zinc-rich and aluminum-rich phases, which may be stained by water, kerosene is used as the lubricant.

Polishing. A light pressure is preferred during all stages of polishing, and each stage of polishing should be continued for at least twice as long as it takes to remove the scratches from the previous stage. Polishing is usually carried out using different grades of diamond suspended in an oil-base vehicle. Every effort must be made to ensure that the polishing wheels and the pads used for diamond pastes are kept free from dust, grit, and the diamond particles from the previous polishing stage. It is essential that coarse grinding and fine polishing be done at different locations; the environment where fine polishing is conducted must be free from corrosive fumes.

Scratches from the 600 grit silicon carbide papers are removed by polishing for several minutes on a wheel covered with a short-nap or napless cloth impregnated with 6 μm diamond paste. Next, the specimen is polished on a wheel covered with a short-nap cloth impregnated with 1 μm diamond paste. Final polishing is conducted using alumina slurries or with colloidal silica. A vibratory polisher is very useful for tin and tin alloys.

Etching

Although the method of polishing is the same for all types of tin and tin alloys, different enchants are used for etching the various alloys (see Table 19).

Table 19 Etchants for use in microscopic examination of tin and tin alloys

Etchant composition	Uses
5 mL HCl, 2 g $FeCl_3$, 30 mL water, 60 mL absolute alcohol	General use for tin and tin alloys
2 mL HCl, 98 mL methanol (95%) or ethanol (95%)	Grain-boundary etch for pure tin
10 mL HNO_3, 10 mL acetic acid, 80 mL glycerol	Darkens the lead in the eutectic of tin-rich tin-lead alloys
5% silver nitrate in water	Darkens primary and eutectic lead in lead-rich tin-lead alloys
2% nital	Recommended for etching tin-antimony alloys; darkens tin-rich matrix, leaving intermetallic compounds unattacked. Often used for etching specimens of babbitted bearings
Picral	For etching tin-coated steel and tin-coated cast iron
1 drop HNO_3 (conc), 2 drops HF, 25 mL glycerol; then picral	For etching tin-coated steel
Dilute ammonium hydroxide with a few drops of 30% hydrogen peroxide	For etching tin-coated copper and copper alloys

Technique for Titanium and Titanium Alloys

PREPARATION OF METALLOGRAPHIC SPECIMENS of unalloyed titanium and of alpha, alpha-beta, and beta titanium alloys is described in this section.

Sectioning

Sectioning of titanium and titanium alloys follows conventional procedures, but deformation and overheating must be avoided. As with the refractory metals, sectioning of titanium and its alloys is more difficult than for most metals. Deformation can result in mechanical twinning and strain-induced transformation products, as well as overheating, in changes in structure. Abrasive cutting with silicon carbide wheels is satisfactory if adequate coolant is used. A very softly bonded wheel is essential for good cuts. Use of bandsaws is common for these alloys. Sectioning using an oil-cooled precision diamond saw is recommended for small specimens to avoid overheating.

Mounting

Titanium and its alloys are mounted in the common materials, such as phenolic, methyl methacrylate, and diallyl phthalate; when edge preservation is important, compression-mounting epoxy is recommended. Nickel plating of specimens before mounting also assists in edge preservation. In general, the temperatures encountered in compression mounting do not cause problems. However, when metallographic examination involves the hydride phase (TiH), it is best to leave the specimen unmounted or to mount it in a low-temperature setting epoxy resin because of the increased solubility of hydrogen in titanium at the higher temperatures. Sometimes, mounting in a thermosetting material can cause solution of existing hydride and, on cooling, precipitation of the hydride in an altered form, usually a fine dispersion. Adding 50 vol% of silica powder (between 200 and 325 grit) to the epoxy resin or nickel plating will aid edge preservation.

Grinding

The traditional procedure for grinding titanium specimens is similar to that for grinding steel specimens. The specimens are ground on successive grades of silicon carbide paper, starting with 120 grit and proceeding to 240, 320, 400, and 600 grit papers, using water to keep the specimens cool and flush away loose particles of metal and abrasive. It is possible to start grinding on a paper with a grit size as coarse as 80 grit (if the cut surface is very rough), provided that pressure is light so as to minimize cold working. Embedment of SiC abrasive particles is a problem with titanium and its alloys. To reduce embedding abrasive particles in the ground surface, the papers may be dressed with solid stick wax; however, it is possible to remove these particles in the subsequent steps. Stationary abrasive sheets or rotating disk and belt grinder devices are used.

Polishing

Manual, automatic, vibratory and electrolytic polishing may be used for specimens of titanium and titanium alloys.

Manual polishing is traditionally is performed in three stages: rough, intermediate, and final polishing. Rough polishing is performed on a high-speed polishing wheel covered with a lintless rayon or silk cloth, using medium pressure and a slurry consisting of 35 mL of water, 15 g of 1 or 3 μm alpha (levigated) alumina, and 5 mL of 20% chromic acid (optional). An alternative procedure for rough polishing is to use a nylon cloth and 6 μm diamond paste. Intermediate polishing is done with the same equipment and procedure, except that 0.3 μm alumina is used in the slurry. Final polishing is performed on a low-speed wheel covered with Microcloth (Buehler, Ltd., Lake Bluff, IL), using a slurry containing 15 g of 0.05 μm alumina and 35 mL of water, and with light pressure on the specimen.

At the start of intermediate polishing, rather heavy pressure is applied. As polishing progresses, pressure is decreased. Several cycles of polishing and etching may be needed to remove flowed metal. Etching should be light to avoid pitting. The specimen is unetched when final polishing starts. Several cycles of polishing and etching may also be necessary during final polishing.

For rough polishing of unalloyed titanium, which is considerably softer than the alloys, use of a wheel covered with 6.4 to 12.7 mm ($\frac{1}{4}$ to $\frac{1}{2}$ in.) of paraffin and a slurry of 3 μm levigated alumina has been recommended. For intermediate polishing, the same wheel may be used with a slurry of 0.3 μm alumina. Final polishing may be performed on a wheel covered with a short-nap cloth and using a slurry of 0.05 μm alumina.

Automatic polishing has an advantage in that the pressure exerted on the specimen can be controlled. Specimens are ground through 180, 240, 320, 400, and 600 grit silicon carbide paper using water or kerosene as the coolant. Final polishing is done using Microcloth and 0.05 μm gamma alumina for about 10 min. Several specimens can be prepared simultaneously.

Vibratory polishing, although a slower process than electrolytic or mechanical polishing, produces excellent results. Vibratory polishing can be a two-stage operation that follows grinding on abrasive papers. Preliminary polishing is performed on a canvas cloth for 2 to 4 h or on a silk cloth for 30 to 45 min, both using a slurry of 0.3 μm alumina. Final polishing is performed on a short-nap cloth for 15 min to 4 h, using a slurry of 0.05 μm alumina. Several short polishing and etching cycles may be used to remove disturbed metal. Colloidal silica also produces very good results. Attack polishing agents are often added to the colloidal silica producing crisper, sharper detail.

Electropolishing is considerably faster than mechanical polishing. An electrolyte recommended for electropolishing contains 600 mL of methanol, 360 mL of ethylene glycol, and 60 mL of perchloric acid. Polishing time is 15 to 25 s at a current density of 1 to 1.5 A/cm^2, depending on specimen size and polishing area. The electrolyte given previously, with a low concentration of perchloric acid, is nonexplosive and can be stored for several weeks. However, care should be exercised in handling concentrated perchloric acid, because it can react explosively with organic materials, such as mounting compounds.

Etching

Macroetching. At least three different etchants are used for macroetching of titanium and titanium alloys. Two of these are general-purpose etchants; the choice between the two is usually arbitrary. One of the general-purpose etchants is composed of equal parts, by volume, of hydrofluoric acid, nitric acid, and water; the other is composed of 5 mL of hydrofluoric acid, 35 mL of nitric acid, and 60 mL of water. An etchant composed of 50 mL of concentrated hydrochloric acid and 50 mL of water is often preferred for macroetching of alpha-beta titanium alloys.

Microetching is accomplished by swabbing or immersion. Because etching by immersion can promote reprecipitation of dissolved alloying elements, such as tin, back onto the specimen surface, it is recommended that both immersion and swabbing techniques be initially evaluated to identify the presence of such etching artifacts. Swabbing usually produces a brighter, clearer etching response than immersion. Etching times are usually short, ranging from 3 to 10 s. The specimen should be examined after light etching to avoid overetching.

Nearly all etchants for titanium and titanium alloys contain hydrofluoric acid and an oxidizing agent, such as nitric acid. Table 20 gives the compositions and purposes of etchants suitable for use on unalloyed titanium and on titanium alloys. Kroll's reagent is the etchant most widely used for commercial titanium alloys.

Table 20 Etchants for microscopic examination of titanium and titanium alloys

Specimen metal	Composition of etchant	Purpose
Unalloyed titanium	1-3 mL HF, 10 mL HNO_3, 30 mL lactic acid	Reveals hydrides
	1 mL HF, 30 mL HNO_3, 30 mL lactic acid	Reveals hydrides
Most titanium alloys	Kroll's reagent: 1-3 mL HF, 2-6 mL HNO_3, water to 1000 mL	General-purpose etch
	10 mL HF, 5 mL HNO_3, 85 mL water	General-purpose etch
	1 mL HF, 2 mL HNO_3, 50 mL H_2O_2, 47 mL water	Removes stain
	10 mL HF, 10 mL HNO_3, 30 mL lactic acid	Chemical polish and etch
	2 mL HF, 98 mL water	Reveals alpha case
	1-2 mL HF, 4-5 mL H_2O_2, water to 1000 mL	Nonstaining etch
Near-alpha titanium alloys	2 mL HF, 98 mL water; then 1 mL HF, 2 mL HNO_3, 97 mL water	General-purpose etch(a)
Alpha-beta titanium alloys	10 mL KOH (40%), 5 mL H_2O_2, 20 mL water	Stains alpha, transformed beta
Ti-Al-Zr and Ti-Si alloys	18.5 g benzalkonium chloride, 33 mL ethanol, 40 mL glycerol, 25 mL HF	General-purpose etch
Ti-3Al-8V-6Cr-4Mo-4Zr	30 mL H_2O_2, 3 drops HF	General-purpose etch
Ti-8Mn; aged Ti-13V-11Cr-3Al	2 mL HF, 4 mL HNO_3, 94 mL water	General-purpose etch
Ti-Si alloys	2 drops HF, 1 drop HNO_3, 3 mL HCl, 25 mL glycerol	General-purpose etch

(a) First etchant stains alpha phase; second etchant removes stain

Technique for Refractory Metals and Alloys

MARKED DIFFERENCES in ductility, abrasion resistance, response to work hardening, and other pertinent properties among the refractory metals (tungsten, molybdenum, niobium, and tantalum) and their alloys necessitate the use of a variety of techniques for preparation of metallographic specimens. A particular product form, such as wire, may also require special preparation techniques.

Tungsten

Sectioning of tungsten and tungsten alloys should be performed using a resinoid-bonded, 70 grit aluminum oxide abrasive wheel, such as A-70-T-B. Wire can be cut with wet or dry abrasive wheels, preferably after a heavy nickel plate has been applied for protection. Nickel plating also aids in edge retention and in keeping the wire sections flat. Because tungsten wire can delaminate, it should never be cut with mechanical wire cutters.

Mounting. Most specimens of tungsten or tungsten alloys are mounted in the same manner as specimens of other metals.

Electrolytic Polishing. Aqueous electrolytes containing 1 to 10% sodium hydroxide or potassium hydroxide can be used successfully for electrolytic polishing of tungsten and tungsten alloys. Usually, a 2 to 4% sodium hydroxide aqueous solution with a nickel cathode is used. Better results may be obtained if half the volume of water in the solution is replaced by glycerol and the sodium hydroxide content is increased to 5%.

Etching. Murakami's reagent, conventional or modified, is most often used for etching tungsten and tungsten alloys, although other etchants are sometimes used (Table 21). In addition to the etchants shown in Table 21, electrolytic etching in a 4% sodium hydroxide aqueous solution, using 1 to 5 A (ac) or 0.5 to 1 A (dc), has been successfully used in some laboratories for improving grain-boundary contrast.

Table 21 Etchants for metallographic specimens of refractory metals

Etchant	Composition
Etchants for tungsten and molybdenum and their alloys	
1 Murakami's reagent	10 g $K_3Fe(CN)_6$, 10 g KOH or NaOH, 100 mL water
2 Murakami's reagent (mod)	15 g $K_3Fe(CN)_6$, 2 g NaOH, 100 mL water
3 Electrolytic	5 mL H_2SO_4, 1 mL HF, 100 mL methanol (95%)
4[(a)]	5 mL HF, 10 mL HNO_3, 30 mL lactic acid
5	15 mL HNO_3, 3 mL HF, 80 mL water
Additional etchants for molybdenum and molybdenum alloys	
6	10 mL HF, 30 mL HNO_3, 60 mL lactic acid
7	25 mL HCl, 10 mL H_2SO_4, 75 mL methanol
Etchants for niobium and tantalum and their alloys	
8	30 mL HF, 15 mL HNO_3, 30 mL HCl
9	10 mL HF, 10 mL HNO_3, 20 mL glycerol
10	5 mL HF, 20 mL HNO_3, 50 mL acetic acid
11	25 mL HNO_3, 5 mL HF, 50 mL water
12	30 mL H_2SO_4, 30 mL HF, 3 to 5 drops H_2O_2 (30%), 30 mL water
13	50 mL HNO_3, 30 g ammonium bifluoride, 20 mL water
Additional etchants for niobium and niobium alloys	
14	20 mL HF, 15 mL H_2So_4, 5 mL HNO_3, 50 mL water
15	30 mL lactic acid, 10 mL HNO_3, 10 mL HF
16	20 mL HNO_3, 10 mL HF, 70 mL water
17	15 mL HCl, 15 mL H_2SO_4, 8 mL HNO_3, 62 mL water
Additional etchants for tantalum and tantalum alloys	
18	10 g NaOH, 100 mL water
19	20 mL HF, 20 mL HNO_3, 60 mL lactic acid
20	10 mL HF, 90 mL H_2SO_4

(a) Procedure: Swab with heavy pressure for 5-10 s, water rinse, alcohol rinse, dry, etch with Murakami's reagent (etchant 1).

Molybdenum

Because molybdenum is relatively soft, scratches and distorted metal developed in sectioning, grinding, and polishing are difficult to eliminate, and therefore electrolytic polishing is commonly used for molybdenum.

Electrolytic Polishing. An excellent polish, particularly with difficult-to-polish alloys, such as TZM, can be obtained using an electrolyte consisting of 12.5% sulfuric acid with a remainder of ethanol or methanol. Nickel is used as the cathode. Voltages between 8 and 50 V dc have been used successfully.

Etching. A modified Murakami's reagent is recommended for etching molybdenum. It provides good grain-boundary contrast and yet minimizes etch pitting. A typical mixture contains 15 g of potassium ferricyanide, 2 g of sodium hydroxide, and 100 mL of water.

Niobium and Tantalum

Specimens of niobium and tantalum and their alloys are prepared by techniques similar to those used for preparing stainless steel specimens.

Polishing. A typical method of rough polishing niobium and tantalum employs a wax wheel and 15 μm levigated alumina. Intermediate polishing is done on a Microcloth-covered wheel using 1 μm alumina, and final polishing is also done on a Microcloth-covered wheel using 0.3 μm alumina.

Etchants used for metallographic specimens of niobium and tantalum and their alloys are listed in Table 21.

Technique for Zinc and Zinc Alloys

METALLOGRAPHIC TECHNIQUES that are special to the preparation of specimens of zinc and zinc alloys are discussed in this section.

Sectioning and Mounting

Sectioning. The initial sample may be removed from a larger mass of material by abrasive cutting, sawing, breaking, or shearing, much the same as for other metals.

Mounting. Specimens of rolled zinc and zinc alloys may be held by clamping; they are not mounted in plastic. Several specimens are mounted together in a screw clamp, with thin spacers of soft zinc between specimens and heavy strips of zinc between the clamp plates and the outermost specimens. The assembly is tightly clamped to prevent seepage of etchants between specimens. The zinc spacers are of known structure and serve as convenient standards of comparison for determining if the specimens have been correctly prepared.

Most specimens other than those of rolled metal are mounted in conventional plastic molding materials. See the description of mounting materials in the section "Metallographic Methods" in the article "Metallographic Practices Generally Applicable to All Metals."

Grinding and Polishing

In grinding and polishing of cast zinc, distortion can occur to a depth 20 to 100 times as great as the deepest scratch. Therefore, in each stage of grinding and polishing, considerably more metal should be removed than the amount required for eliminating the scratches that remain from the previous stage. It is easier to prepare a distortion-free surface on specimens of fine grain zinc than on specimens of coarse grain, soft zinc.

Traditional grinding is done with silicon carbide papers using successively finer grit sizes of 180, 240, 320, 400, and 600 mesh. These papers are less susceptible to loading than emery papers. Grinding can be done by hand on papers supported on a flat surface, or by holding the specimen against the same grades of paper on a grinding wheel. Overheating of the specimen during wheel grinding should be minimized. This problem can be solved by using a low wheel speed (300 rpm max), by applying water to the silicon carbide papers during grinding, and by grinding in intervals of a few seconds and allowing the specimen to cool between intervals before grinding is resumed.

Rough polishing may be performed using 6-μm diamond charged onto napless, low-nap or medium-nap cloths. Final polishing can be done using alumina or magnesium oxide slurries on medium-nap cloths. Colloidal silica is excellent for final polishing of zinc alloys but may cause pitting of pure zinc.

Macroetching

Use of concentrated hydrochloric acid at room temperature, followed by rinsing and wiping off the resulting black deposit, produces good grain contrast on copper-free zinc and zinc alloys. Etchant 1 in Table 22 may be used for zinc containing 1% Cu or less. With this etchant, grain contrast is not well defined. An etchant equal to hydrochloric acid for producing grain contrast has not been found for zinc alloys containing copper.

Table 22 Etchants for zinc and zinc alloys

Etchant	Composition
1[a]	200 g CrO_3, 15 g Na_2SO_4, 1000 mL water
2[b]	50 g CrO_3, 4 g Na_2SO_4, 1000 mL water
3	200 g CrO_3, 1000 mL water

(a) For rolled zinc-copper alloys, the Na_2SO_4 content can be reduced to 7.5 g. If desired, a smoothly etched surface can be obtained by increasing the Na_2SO_4 to 30 g.

(b) This etchant can be made by mixing one part (by volume) of etchant 1 and three parts of water.

Microetching

The most useful etchants for microscopic examination of zinc and zinc alloys are aqueous solutions of chromic acid (CrO_3, or chromic anhydride) to which sodium sulfate (Na_2SO_4) has been added. Grades of chromic acid used for chromium plating are satisfactory. Table 22 gives compositions of etchants commonly used.

Etching should follow soon after final polishing. The specimen should be cleaned in alcohol and then in running water and etched while still wet. To avoid staining, the use of etchant 1 or 2 in Table 22 should be followed immediately by a rinse in etchant 3. The specimen is then thoroughly washed in running water, dipped in alcohol, and dried with a stream of warm, clean air.

Table 23 gives recommendations for etchants and etching times for zinc and zinc die-casting alloys. The etching time may be longer or shorter for specific etching conditions (a minor difference in solution temperature may affect etching time). Also, as indicated in Table 23 for cast or rolled zinc, etching time is often decreased as the magnification to be used in increased.

Table 23 Etchants and etching times for zinc and zinc die-casting alloys

Specimen metal	Etchant (from Table 22)	Etching time, s, for examination at:	
		250×	**1000×**
Cast or rolled zinc	1	5	1
Alloy AC41A or AG40A	2	1	1

Measurement of Microstructure

Edited by George F. Vander Voort, Buehler Ltd.

Introduction

QUANTIFYING MICROSTRUCTURAL PARAMETERS has received considerable attention in recent years and success in developing procedures and using such data to develop structure/property relationships has been achieved. Chart methods for rating microstructures have been used for many years to evaluate microstructures, chiefly for conformance to specifications. At this time, true quantitative procedures have not replaced chart methods for such purposes, but they have gained wide usage in quality control and research studies. Examples of the applications of quantitative metallography have been reviewed by Underwood (Ref 1).

Basically, two types of measurements of microstructures are made. The first group includes measurements of depths (i.e., depth of decarburization, depth of surface hardening, or coating thicknesses). These measurements are made at a specific location (the surface) and may be subject to considerable variation. To obtain reproducible data, these surface conditions must be measured at a number of positions on a given specimen, and on several specimens if the material being sampled is rather large.

The second group of measurements belongs to the field referred to as stereology. This body of measurements describes the relationship between measurements made on the two-dimensional plane of polish and the three-dimensional microstructural features sampled. To facilitate communications, the International Society for Stereology (ISS) has proposed a standard system of notation, as shown in Table 1 (Ref 2).

Table 1 Standard notation recommended by International Society for Stereology

Symbol	Units	Description	Common name
P	. . .	Number of point elements or test points	. . .
P_P	. . .	Point fraction (number of point elements per total number of test points)	Point count
L	mm	Length of linear elements or test-line length	. . .
P_L	mm^{-1}	Number of point intersections per unit length of test line	. . .
L_L	mm/mm	Sum of linear intercept lengths divided by total test-line length	Lineal fraction
A	mm^2	Planar area of intercepted features or test area	. . .
S	mm^2	Surface area or interface area, generally reserved for curved surfaces	. . .
V	mm^3	Volume of three-dimensional structural elements or test volume	. . .
A_A	mm^2/mm^2	Sum of areas of intercepted features divided by total test area	Areal fraction
S_V	mm^2/mm^3	Surface or interface area divided by total test volume (surface-to-volume ratio)	. . .
V_V	mm^3/mm^3	Sum of volumes of structural features divided by total test volume	Volume fraction
N	. . .	Number of features	. . .
N_L	mm^{-1}	Number of interceptions of features divided by total test-line length	Lineal density
P_A	mm^{-2}	Number of point features divided by total test area	. . .
L_A	mm/mm^2	Sum of lengths of linear features divided by total test area	Perimeter (total)
N_A	mm^{-2}	Number of interceptions of features divided by total test area	Areal density
P_V	mm^{-3}	Number of points per test volume	. . .
L_V	mm/mm^3	Length of features per test volume	. . .
N_V	mm^{-3}	Number of features per test volume	Volumetric density
$\overline{L}$	mm	Mean linear interception distance, L_L/N_L	. . .
$\overline{A}$	mm^2	Mean area intercept, A_A/N_A	. . .
$\overline{S}$	mm^2	Mean particle surface area, S_V/N_V	. . .
$\overline{V}$	mm^3	Mean particle volume, V_V/N_V	. . .

Note: Fractional parameters are expressed per unit length, area or volume.

Source: Ref 2

These measurements are made manually with the aid of templates outlining a fixed field area, systems of straight or curved lines of known length, or a number of systematically spaced points. The simple counting measurements, P_P, P_L, N_L, P_A, and N_A, are most important and are easily made. These measurements are useful by themselves and can be utilized to derive other important relationships. These measurements can also be made using semiautomatic or automatic image analyzers.

References

1. E.E. Underwood, Applications of Quantitative Metallography, *Metallography, Structures, and Phase Diagrams,* Vol 8, *Metals Handbook,* 8th ed., American Society for Metals, 1973, p 37-47
2. E.E. Underwood, *Quantitative Stereology,* Addison-Wesley, 1970

Volume Fraction

One of the simplest and most useful measurements is the point count (described in ASTM E 562) used to estimate volume fractions of microstructural constituents. While other manual procedures can be employed, the point count is most efficient--it gives the best accuracy with minimum effort (Ref 3). To perform this test, a clear plastic grid with a number of systematically spaced points (usually crosses are employed, where the "point" is the intersection of the arms), typically 9, 16, 25, 49, 64, or 100, is placed on a micrograph, on a projection screen, or inserted as an eyepiece reticle. The number of points lying on the phase or constituent of interest is counted and divided by the total number of grid points. Points lying on a boundary are counted as half-points. This procedure is repeated on a number of fields selected without bias (without looking at the image).

The point fraction, P_P, is given by:

$$P_P = P_\alpha / P_T \qquad \textbf{(Eq 1)}$$

where P_α is the number of grid points lying inside the feature of interest, α, plus one-half the number of grid points lying on particle boundaries, and P_T is the total number of grid points. Studies have shown that the point fraction is equal to the area fraction, A_A, and volume fraction, V_V, of the second-phase particles:

$$P_P = A_A = V_V \qquad \textbf{(Eq 2)}$$

The volume fraction can also be estimated by dividing the total length of linear elements of a test pattern lying within the phase by the total length of the test pattern. The lineal fraction, L_L, is also equal to the parameters in Eq 2. Point counting is always performed on the minor phases--where V_V = 0.5. The amount of the major (matrix) phase can be determined by difference.

The fields measured should be selected at locations over the entire polished surface, not confined to a small portion of the specimen surface. The field measurements should be averaged, and the standard deviation can be used to assess the relative accuracy of the measurement, as described in ASTM E 562.

In general, the number of points on the grid should be increased as the volume fraction of the feature of interest decreases. One study (Ref 3) suggested that the optimum number of grid test points is $3/V_V$. Hence, for volume fractions of 0.5 (50%) and 0.01 (1%), the optimum numbers of grid points are 6 and 300, respectively. If the structure is heterogeneous, measurement accuracy is improved by using a low-point-density grid and increasing the number of fields measured.

Figure 1 demonstrates the point counting procedure and shows a synthetic microstructure consisting of 24 circular particles, each 6 mm in diameter, within a field area of 12,100 mm^2. The total area of the circular particles is 678.6 mm^2, which is an area fraction of 0.056 (5.6%). A square grid pattern has been drawn over this field, producing 100 intersection points. Four of these intersections are completely within the particles and four lie on the particle interface. The number of "hits" is, therefore, $4 + \frac{1}{2}(4) = 6$. Thus, P_P is $\frac{6}{100}$ or 0.06 (6%), which agrees very closely with the theoretically calculated area fraction. The area fraction, A_A, is equal to the volume fraction, V_V, as long as the sectioning plane intersects the structural features at random.

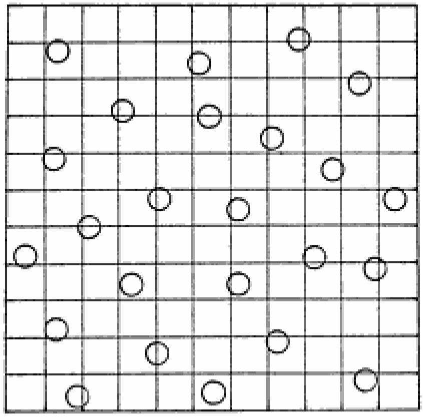


Fig. 1 Synthetic microstructure of uniformly shaped, identical size spherical particles in a matrix phase. Test area is 12,100 mm^2. Test lines, ten horizontal and ten vertical, are 110 mm long.

Reference cited in this section

3. J.E. Hilliard and J.W. Cahn, An Evaluation of Procedures in Quantitative Metallography for Volume-Fraction Analysis, *Trans. AIME,* Vol 221, April 1961, p 344-352

Number per Unit Area

The count of the number of particles within a given measurement area, N_A, is a useful microstructural parameter and is used in other calculations. Referring again to Fig. 1, there are 24 particles in the measurement area (12,100 mm^2). Hence, the number of particles per unit area, N_A, is 0.00198 mm^{-2}. The average area of the particles can be calculated by dividing the volume fraction, V_V, by N_A:

$$A = V_V/N_A \qquad \textbf{(Eq 3)}$$

This yields an average area, A, of 28.23 mm^2, which agrees well with the calculated area of a 6 mm diameter particle of 28.27 mm^2. The above example illustrates the calculation of the average area of particles in a two-phase microstructure.

P_L and N_L

Counting of the number of intersections of a line of known length with particle or grain features, P_L, or the number of interceptions of particles or grains by a line of known length, N_L, provides two very useful microstructural parameters. For space-filling grain structures (single phase), $P_L = N_L$, while for two-phase structures, $P_L = 2N_L$ (this may differ by one count in actual cases).

Grain-Structure Measurements. For single-phase grain structures, it is usually easier to count the grain-boundary intersections with a line of known length. This is the basis of the Heyn intercept grain-size procedure described in ASTM E 112. For most work, a circular test grid composed of three concentric circles with a total line length of 500 mm is preferred. Grain size is defined by the mean lineal intercept length, l:

$$l = 1/P_L = 1/N_L \qquad \textbf{(Eq 4)}$$

This equation must be modified, as described later, for two-phase structures. To calculate the ASTM grain size number, l can be used.

P_L measurements can be utilized to define the surface area per unit volume, S_V, and the length per unit area, L_A, of grain boundaries:

$$S_V = 2P_L \qquad \textbf{(Eq 5)}$$

and

$$L_A = (\pi/2)(P_L) \qquad \textbf{(Eq 6)}$$

For single-phase structures, P_L and N_L are equal, and either measurement can be used. For two-phase structures, it is best to measure P_L to determine the phase-boundary surface area per unit volume, or phase-boundary length per unit area.

Oriented Structures. Measurements of P_L are utilized to assess the degree of orientation of lines or surfaces. Certain microstructures exhibit a high degree of preferred directionality on the plane of polish or within the sample volume. A structure is completely oriented if all of its elements are parallel. Partially oriented systems are those with features having both random and oriented elements. To assess the degree of orientation, the plane of polish must be longitudinal, planar, or transverse with respect to the deformation axis.

Several approaches can be utilized to assess the degree of orientation of a microstructure. For single-phase grain structures, a simple procedure is to make P_L measurements parallel and perpendicular to the deformation axis on a longitudinally oriented specimen. The degree of grain orientation is the ratio of perpendicular to parallel P_L values--i.e., $P_{L\perp}/P_{L\parallel}$. Another very useful procedure is to calculate the degree of orientation, Ω, using these P_L values:

$$\Omega = (P_{L\perp} - P_{L\parallel})/(P_{L\perp} + 0.571P_{L\parallel}) \qquad \textbf{(Eq 7)}$$

To illustrate these measurements, a section of low-carbon steel sheet was cold rolled to reductions in thickness of 12, 30, and 70%. $P_{L\perp}$ and $P_{L\parallel}$ measurements were made using a grid with parallel straight test lines on a longitudinal section from each of four specimens (one specimen for each of the three reductions, plus one specimen of as-received material). Table 2 gives the results, which indicate that cold working produces an increased orientation of the grains in the longitudinal direction.

Table 2 Degrees of grain orientation for four samples of low-carbon steel sheet

Sample	$P_{L\perp}$ (a)	$P_{L\parallel}$ (a)	$P_{L\perp}/P_L$ (a)	Ω, %
As-received	114.06	98.86	1.15	8.9
Cold rolled				
12% reduction	126.04	75.97	1.66	29.6
30% reduction	167.71	60.6	2.77	52.9
70% reduction	349.4	34.58	10.1	85.3

(a) Number of grain-boundary intersections per millimeter

Spacings. N_L measurements are utilized in the study of the spacing of two-phase structures. One of the most common spacing measurements is that of lamellar pearlite or other eutectoid or eutectic structures (Ref 4). The true interlamellar spacing, σ_t, is difficult to measure, but the mean random spacing, σ_r, is readily assessable and is directly related to the mean true spacing:

$$\sigma_t = \sigma_r/2 \qquad \textbf{(Eq 8)}$$

The mean random spacing is determined by placing a test grid consisting of one or more concentric circles on the pearlite lamellae in an unbiased manner. The number of interceptions of the carbide with the test line(s) is counted and divided by the true length of the test line, to obtain N_L. The reciprocal of N_L is the mean random spacing:

$$\sigma_r = 1/N_L \qquad \textbf{(Eq 9)}$$

The mean true spacing, σ_t, is $\frac{1}{2}\sigma_r$. To make accurate measurements, the lamellae must be clearly resolved; hence, use of transmission electron microscope replicas is quite common.

Measurements of N_L are also used to measure interparticle spacings in two-phase alloys. The mean center-to-center spacing of particles, σ, is the reciprocal of N_L. For the second-phase particles in the idealized two-phase structure shown in Fig. 1, a count of the number of particles intercepted by the horizontal and vertical test lines yields 31 interceptions. The total line length is 2200 mm; hence, $N_L = 0.0141$ mm^{-1} and $\sigma = 70.9$ mm.

The mean edge-to-edge distance between such particles, known as the mean free path, λ, is determined in like manner but requires knowledge of the volume fraction of the particles. The mean free path is calculated:

$$\lambda = (1 - V_V)/(N_L) \qquad \textbf{(Eq 10)}$$

For the structure shown in Fig. 1, the volume fraction of the particles was estimated as 0.056. Hence, $\lambda = 66.95$ mm.

The mean lineal intercept distance, l_α, for these particles is determined by:

$$l_\alpha = \sigma - \lambda \qquad \textbf{(Eq 11)}$$

For this example, $l_\alpha = 3.95$ mm. This value is smaller than the caliper diameter of the particles, because the test lines intercept the particles at random, not only at the maximum dimension.

Reference cited in this section

4. G.F. Vander Voort and A. Roosz, Measurement of the Interlamellar Spacing of Pearlite, *Metallography,* Vol 17, Feb 1984, p 1-17

Grain Size

Perhaps the most common quantitative microstructural measurement is that of the grain size of metals and alloys. Numerous procedures have been developed to estimate grain size; these procedures are summarized in detail in ASTM E 112 and illustrated in Ref 5. Several types of grain sizes can be measured: ferrite grain size, austenite grain size, and prior-austenite grain size. Each type presents particular problems associated with revealing these boundaries so that an accurate rating can be obtained (Ref 5). To complicate matters, a variety of parameters are utilized to define grain size:

- Average grain diameter, d
- Average grain area, A
- Number of grains per unit area, N_A
- Average intercept length, l
- Number of grains intercepted by a line of fixed length
- Number of grains per unit volume, N_V

- Average grain volume, V

These parameters can be related to the ASTM grain size number, G.

The ASTM grain-size scale was established using the Imperial system of units, but no difficulty is introduced by metric measurements. The ASTM grain size equation is:

$$n = 2^{G-1} \qquad \textbf{(Eq 12)}$$

where n is the number of grains per square inch at 100×. Multiplication of n by 15.5 gives the number of grains per square millimeter at 1×, N_A.

Planimetric Method. The oldest procedure for measuring the grain size of metals is the planimetric method. A circle of known size (generally 79.8 mm diameter, 5000 mm^2 area) is drawn on a photomicrograph or used as a template on a projection screen. The number of grains completely within the circle, n_1, and the number of grains intersecting the circle, n_2, are counted. For accurate counts, the grains must be marked off as they are counted, which makes this method slow. The number of grains per square millimeter at 1×, N_A, is determined:

$$N_A = f(n_1 + n_2/2) \qquad \textbf{(Eq 13)}$$

where f is the magnification squared divided by 5000 (the circle area). The average grain area, A, in square millimeters, is:

$$A = 1/N_A \qquad \textbf{(Eq 14)}$$

and the average grain diameter, d, in millimeters, is:

$$d = (A)^{1/2} = 1/(N_A)^{1/2} \qquad \textbf{(Eq 15)}$$

The ASTM grain size, G, can be found by using the tables in ASTM E 112 or by the following equation:

$$G = 3.322(\log N_A) - 2.95 \qquad \textbf{(Eq 16)}$$

Figure 2 illustrates the planimetric method. Expressing grain size in terms of d is being discouraged by ASTM Committee E-4 on Metallography, because the calculation implies that grain cross sections are square, which they are not.

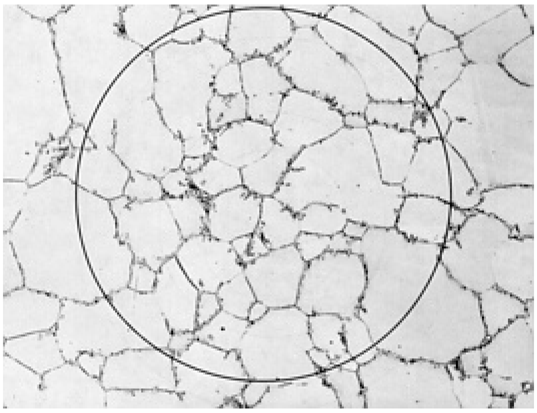


Fig. 2 Example of grain size measurement by the planimetric method. Micrograph, at 100×, of an austenitic manganese steel that was solution annealed at 1040 °C (1900 °F) and aged at 620 °C (1150 °F) to decorate

the grain boundaries with fine pearlite. The circle has a diameter of 79.8 mm, for an area of 5000 mm^2. A count is made to determine the number of grains completely within the circle (44) and the number intersecting the circle (25). The planimetric multiplier for 100× is 2. The number of grains per square millimeter at 1× is (2)(44 + 25/2) = 113. The ASTM grain size, G, is (3.322 log 113) - 2.95 = 3.87 (round to 3.9 or 4).

The intercept method is faster than the planimetric method because the micrograph or template does not require marking to obtain an accurate count. ASTM E 112 recommends use of a template consisting of three concentric circles with a total line length of 500 mm (template available from ASTM). The template is placed over the grain structure without bias, and the number of grain-boundary intersections, P, or the number of grains intercepted, N, is counted. Dividing P or N by the true line length, L, gives P_L or N_L, which are identical (N or P can differ slightly due to tangent hits) for a single-phase grain structure. It is usually easier to count grain-boundary intersections for single-phase structures. If a grain boundary is tangent to the line, it is counted as $\frac{1}{2}$ of an intersection. If a triple-point line junction is intersected, it is counted as $1\frac{1}{2}$ or 2. The latter is preferred because the small diameter of the inner circle introduces a slight bias to the measurement that is offset by weighing triple-line intersections as 2 hits.

The mean lineal intercept length, l, determined as shown in Eq 4, is a measure of ASTM grain size. It is smaller than d, because the test lines do not intersect each grain at its maximum breath. The ASTM grain size, G, can be determined by use of the tables in ASTM E 112 or can be calculated:

$$G = -6.644 (\log l) - 3.288 \qquad \textbf{(Eq 17)}$$

where l is in millimeters. Figure 3 shows the intercept method for a single-phase alloy.

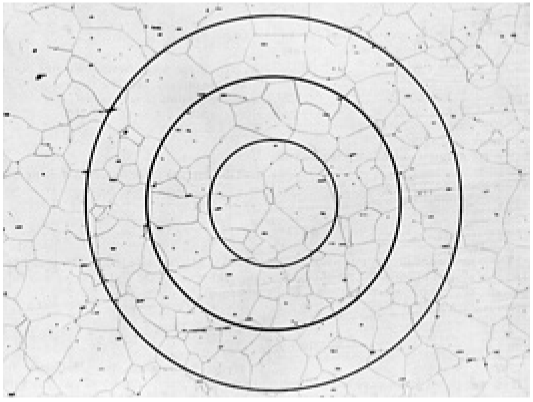


Fig. 3 Example of grain size measurement using the intercept method. The three concentric circles have diameters of 79.5, 47.8, and 31.8 mm, for a total line length of 500 mm. The magnification of this micrograph is 500×, and hence the true line length is 1 mm. A count of the number of grain-boundary intersections (several are not well delineated by the nital etch--a common problem in such ratings, especially if automated devices are used) revealed 60 grain-boundary intersections and 7 triple line-junction intersections. Hence, P = 7(1.5) + 60 = 70.5, and P_L = 70.5 / 1 mm = 70.5/mm. Therefore, l = 1/P_L = 0.0142 mm. The ASTM grain-size number can be evaluated using Eq 17: G = -6.6457(log 0.0142) - 3.298 = 8.98 (round to 9).

Nonequiaxed grain structures require measurements on the three principle planes: the longitudinal, planar, and transverse. For such structures, the intercept method is preferred, but the test grid should consist of a number of straight, parallel test lines of known length rather than circles. Because the ends of the straight lines generally end within grains, these interceptions are counted as half-hits. Three mutually perpendicular orientations are evaluated using grain-interception counts:

- N_{Ll}--parallel to the grain elongation, longitudinal plane
- N_{Lt}--perpendicular to the grain elongation (through-thickness direction), transverse plane

- N_{LP}--perpendicular to the grain elongation (across width), planar surface

The average N_L value is obtained from the cube root of the product of the three directional N_L values. G is determined by reference to the tables in ASTM E 112 or by use of Eq 17 (l is the reciprocal of N_L, Eq 4).

Two-Phase Grain Structures. The grain size of a particular phase in a two-phase structure requires determination of the volume fraction of the phase of interest, such as by point counting. The minor phase (second phase) is point-counted and the volume fraction of the major phase (matrix phase) is determined by difference.

Next, a circular test grid is applied to the microstructure without bias and the number of grains of the phase of interest intercepted by the test line, N_α, is counted. The mean lineal intercept length of the alpha grains, l_α is determined by:

$$l_\alpha = [(V_V)(L/M)]/N_\alpha \qquad \textbf{(Eq 18)}$$

where L is the line length and M is the magnification. The ASTM grain size number can be determined from the tables in ASTM E 112 or by use of Eq 17. The method is shown in Fig. 4.

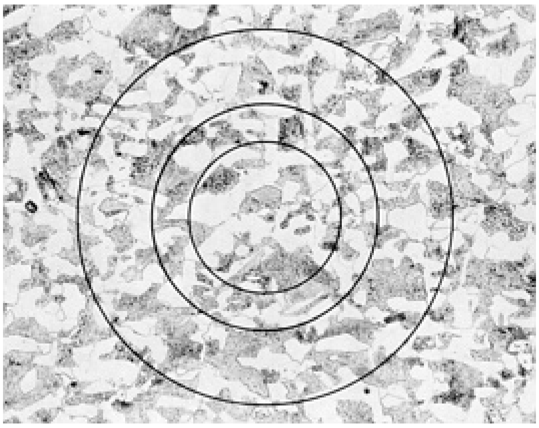


Fig. 4 Example of grain size measurement for a two-phase alloy using point counting and intercept counting. Micrograph, at 500×, of a specimen of alloy Ti-6Al-2Sn-4Zr-2Mo that was forged at 955 °C (1750 °F) in the alpha-beta region and annealed at 970 °C (1775 °F) in the alpha-beta region, producing primary alpha (white) and an alpha-beta eutectoid. The specimen was etched with Kroll's reagent. Point counting was used to determine the amount of equiaxed alpha (48.5%). The three concentric circles have a total circumference of 500 mm. A count is made of the number of equiaxed alpha grains intercepted by the three circles (76). The mean lineal intercept, l_α, is calculated as follows: $l_\alpha = (0.485)(500/500)/76 = 0.006382$ mm. The ASTM grain size, G, is calculated using Eq 17: $G = -6.646(\log 0.006382) - 3.298 = 11.29$ (round to 11.3 or 11.5).

Reference cited in this section

5. G.F. Vander Voort, Grain Size Measurement, *Practical Applications of Quantitative Metallography,* STP 839, American Society for Testing and Materials, 1984, p 85-131

Inclusion Content

Assessment of inclusion types and contents is commonly performed on high-quality steels. Production evaluations utilize comparison chart methods such as those described in ASTM E 45, SAE J422a, or the German standard SEP 1570 (DIN 50602). In these chart methods, the inclusion pictures are defined by type and graded by severity (amount). Either qualitative procedures (worst rating of each type observed) or quantitative procedures (all fields in a given area rated) are employed. Only the Japanese standard JIS-G-0555 uses actual volume fraction measurements for rating of inclusion content (although the statistical significance of the data is questionable).

Manual measurement of the volume fraction of inclusions requires substantial effort to obtain acceptable measurement accuracy due to the rather low volume fractions usually encountered (Ref 6). Consequently, extensive use of image analyzers has been made to overcome this problem. Image analyzers separate the oxide and sulfide inclusions on the basis of their gray-level differences. By using automated stage movement and autofocusing, enough field measurements can be made in a relatively short time to obtain good statistical accuracy. Image analysis is also employed to measure the length of inclusions or to determine stringer lengths.

Two image analysis based standards have been developed, ASTM E 1122 and E 1245. E 1122 produces JK ratings that overcome some of the weaknesses of manual JK ratings. E 1245 is a stereological approach defining, for oxides and sulfides, the volume fraction (V_V), number per unit area (N_A), average length, average area, and the mean free path (spacing in the through-thickness direction). These data are easily databased and statistical in that means and standard deviations are developed so that data can be compared.

Reference cited in this section

6. G.F. Vander Voort, Inclusion Measurement, *Metallography as a Quality Control Tool,* Plenum Press, 1980, p 1-88

Measurement Statistics

In performing stereological measurements, it is necessary to make these measurements on a number of fields and average the results. Measurements on a single field may not be representative of the bulk conditions, because few (if any) materials are sufficiently homogeneous. Calculation of the standard deviation of the field measurements gives a good indication of measurement variability. Calculation of the standard deviation can be done quite simply with an inexpensive pocket calculator.

A further refinement of statistical analysis is calculation of the 95% confidence limit based on the standard deviation, *s*, of the field measurements. The 95% confidence limit is calculated:

$$95\%\ \text{CL} = ts/N^{1/2} \qquad \textbf{(Eq 19)}$$

where *t* is the student's *t* value that varies with *N*, the number of measurements. Many users standardize on a single value of *t*, 2, for calculations irrespective of *N*. The measurement value is expressed as the average *X* ± the 95% CL value. This means that if the test were conducted 100 times, the average values would be between plus and minus the average, *X*, in 95 of the measurements. Next, one can calculate the relative accuracy, % RA, of the measurement:

$$\%\ \text{RA} = (95\%\ \text{CL})X \qquad \textbf{(Eq 20)}$$

Usually, a 10% relative accuracy is considered to be adequate. DeHoff (Ref 7) has developed a simple formula to determine how many fields, *N*, must be measured to obtain a specific desired degree of relative accuracy at the 95% confidence limit:

$$N = [(200/\%\text{RA}) - (S/X)]^2 \qquad \textbf{(Eq 21)}$$

Reference cited in this section

7. R.T. DeHoff, Quantitative Metallography, *Techniques of Metals Research,* Vol II, Part 1, Interscience, 1968, p 221-253

Image Analysis

The measurements described in this brief review and other measurements not discussed can be made by use of automatic image analyzers. These devices rely primarily on the gray level of the image on the television monitor to detect the desired features. In some instances, complex image editing can be utilized to aid separation. Some structures, however, cannot be separated completely; and for these structures, the semiautomatic digital tracing devices can be utilized to improve measurement speed.

Summary

This article reviews many of the simple stereological counting measurements and simple relationships based on these parameters. More complex measurements are discussed at length in Ref 2. The measurements described are easy to learn and use. Their application enables the metallographer to discuss microstructures in a more quantitative manner and reveals relationships between the structure and properties of the material.

Reference cited in this section

2. E.E. Underwood, *Quantitative Stereology,* Addison-Wesley, 1970

Introduction and Overview of Materials Characterization

K.H. Eckelmeyer, Microstructural Analysis Department, Sandia National Laboratories

Introduction

WHY CHARACTERIZE MATERIALS? The macro, micro, and surface composition and structure of materials are determined by their processing and service histories. These conditions, in turn, control material properties and performance. Characterization of a material's composition and structure at these levels provides important information that can be used for several purposes:

- *Quality assurance:* to determine whether processing is done properly
- *Failure analysis:* to determine why properties and performance are different than expected
- *Research and product improvement:* to develop an understanding of how processing and service history influence properties and performance, and use this understanding to develop improved materials

This Section describes the principles and applications of a limited number of techniques that are most commonly used to characterize the composition and structure of metals used in engineering systems. More detailed descriptions of a wider range of characterization techniques are given in *Materials Characterization,* Volume 10, *ASM Handbook,* 1986.

Classification of Materials Characterization Methods

Two useful ways of classifying materials characterization techniques are by the type of information they obtain and the characteristic sample dimensions from which this information is obtained.

When classified by the types of information they obtain, techniques are often classified as the following:

- *Elemental:* What elements are present (qualitative elemental analysis)? In what concentration is each element present (quantitative elemental analysis)?
- *Structural:* How are the atoms crytallographically arranged and spaced? In the case of organic materials, what is the molecular structure?
- *Morphological:* What are the sizes, shapes, arrangements, and appearances of key features, such as grains, cracks, welds, and interfaces?

When classified by the dimensions of material sampled, techniques are frequently categorized as the following:

- *Bulk:* information typically obtained and integrated over surface dimensions on the order of 10^{-2} m or more and depths of at least 50×10^{-6} m, presumably characteristic of the bulk material
- *Micro:* able to obtain information from individual microstructural features, typically able to resolve and characterize features with dimensions of 10^{-6} m or less
- *Surface:* information obtained only from the first atomic layer or so of the sample, such as sampling depths on the order of 10^{-9} m

Table 1 provides an overview of the primary techniques described in this Handbook in terms of these classification schemes. While these methods have been selected primarily based on their applicability to metals, most of them are also readily applicable to other types of inorganic materials, such as ceramics and geologic materials. Polymers and other organic materials are frequently characterized using different analytical techniques.

Table 1 Classification of characterization methods most commonly used with metals

Type of analysis	Information obtained/method		
	Elemental	**Structural**	**Morphological**
Bulk	X-ray fluorescence spectroscopy (XRF) Optical emission spectroscopy (OES) Combustion/inert fusion analysis (LECO)	X-ray diffraction (XRD)	Macrophotography[(b)]
Micro	Scanning electron microscopy (SEM) Electron probe microanalysis (EPMA) Transmission electron microscopy (TEM)	Transmission electron microscopy (TEM) Scanning electron microscopy (SEM)[(a)]	Metallography (MET)[(b)] Scanning electron microscopy (SEM) Electron probe microanalysis (EPMA) Transmission electron microscopy (TEM)

(a) SEM has not historically been capable of this type of analysis, but recent developments are extending SEM capabilities in this area.

(b) Described in the Section "Metallography" in this Handbook.

Selection of Materials Characterization Methods

It is very important to keep the previously described categories in mind when selecting appropriate analytical techniques. There is no universal characterization method that tells everything anyone might want to know about a sample. For each problem, a decision must be made regarding the type of information needed. Based on this, a selection must be made of one or more analytical techniques that will provide this information.

Selection and use of inappropriate methods can result in data that are analytically correct but inappropriate to the problem at hand. This misuse usually confounds the problem rather than helps solve it. For example, it would be inappropriate to use a bulk analysis technique in an effort to identify a thin layer of surface contamination on a material. The results would reflect the composition of the underlying material, not the contamination on its surface. Conversely, it would be equally inappropriate to use a surface analytical technique to determine the bulk composition of an alloy. The results would reflect whatever contaminants happened to be present on the surface, rather than the composition of the underlying alloy. In selecting analytical techniques, it is critically important to think through the current problem, determine what type of information is needed, and select one or more analytical techniques that will provide appropriate types of information. Table 1 provides a key resource in this process.

In addition, in cases where several different types of analyses may be needed to solve a problem, it is important to consider the order in which these analyses are performed, as some types of analysis are destructive or alter the sample, making subsequent types of analysis impossible.

Introduction to Descriptions of Individual Methods

The following articles provide descriptions of the methods most commonly used for characterizing metals. This information is organized into four sections, as represented in Table 1: bulk elemental characterization, bulk structural characterization, microstructural characterization, and surface characterization.

Bulk elemental and bulk structural characterization, which are done using distinctly different techniques, are described in the articles "Bulk Elemental Analysis" and "X-Ray Diffraction for Bulk Structural Analysis," respectively. Many microstructural and surface characterization techniques, described in the articles "Microstructural Analysis" and "Surface Analysis," provide a combination of high resolution imaging of the morphologies of small features plus elemental and/or structural characterization of these features. In many cases, the elemental and structural characterizations done on a micro or surface scale are based on similar principles to those employed in bulk analysis. Hence, to obtain the most complete understanding, the reader is encouraged to read each of these articles in order.

For each method listed in Table 1, a brief overview is provided of the method's capabilities, typical uses and applications, resolution, sensitivity, precision, limitations, sample requirements, operating principles, and capabilities of related techniques. The descriptions of operating principles have been simplified to avoid the more complex physics and chemistry involved. More formal technical descriptions are available in *Materials Characterization,* Volume 10, *ASM*

Handbook, 1986, and in other texts. In cases where the same physical principles are exploited by multiple techniques, these principles are described only in the first technique described. The reader is then referred back to this description in subsequent articles. No descriptions of macrophotography or metallography (light microscopy) are given in this Section; these are covered in the Section "Metallography" in this Handbook.

Bulk Elemental Analysis

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Introduction

THE OVERALL CHEMICAL COMPOSITION of metals and alloys is most commonly determined by x-ray fluorescence (XRF) and optical emission spectroscopy (OES). While these methods work well for most elements, they are not useful for dissolved gases and some nonmetallic elements that can be present in metals as alloying or impurity elements. High-temperature combustion and inert gas fusion methods are typically used to analyze for dissolved gases (oxygen, nitrogen, hydrogen) and, in some cases, carbon and sulfur in metals.

X-Ray Fluorescence Spectroscopy (XRF)

Capabilities

- Detection and quantification of elements with atomic number 5 or higher (older energy dispersive units with beryllium window detectors are limited to atomic number 11 or higher)

Typical Uses

- Qualitative and quantitative chemical analysis for major and minor elements in metals and alloys
- Determination of composition and thickness of thin film deposits

Detection Threshold and Precision: Energy Dispersive Detectors

- Threshold sensitivity: ~0.02%
- Precision of quantitative analyses: ~1% relative or 0.02% absolute, depending on count time

Detection Threshold and Precision: Wavelength Dispersive Detectors

- Threshold sensitivity: ~0.005%
- Precision of quantitative analyses: ~0.2% relative or 0.005% absolute, whichever is greater

Amount of Material Sampled

- *Powders:* Typically several grams pressed into a pellet
- *Bulk solids:* Typically ~1 cm diameter spot on surface, sampling depth from 10 to 100 μm (increases with decreasing average atomic number of sample). Some instruments are designed to map compositional variations, such as segregation in cross-sectioned ingots. These instruments have variable beam diameters down to ~0.1 mm, and *x-y* stages to translate the sample under the beam.

Limitations

- Elements with low atomic numbers produce very few x-rays and are difficult to detect or quantify, particularly in energy dispersive systems. Wavelength dispersive instruments can go down to atomic number 5 (boron). Modern energy dispersive systems are limited to atomic number ~7 (nitrogen) and above. Older energy dispersive systems cannot readily analyze for elements with atomic number less than 11 (sodium).

- Some combinations of elements are difficult to analyze because of overlapping x-ray energies. Such problems sometimes can be overcome by using wavelength dispersive spectrometers, rather than energy dispersive detectors, or by using optical emission spectroscopy (see the section "Capabilities of Related Techniques" in this article).

Sample Requirements

- Bulk metal samples typically are ground to produce a flat uncontaminated surface for analysis. Typical samples have dimensions of several centimeters; however, most instruments can accommodate samples 10 cm or more in diameter.
- Powder samples are typically attached to a non-x-ray producing substrate or are pressed into pellets.
- The technique is completely nondestructive.

Operating Principles

Physical Basis. The negatively charged electrons surrounding each atom's nucleus exist in discrete energy levels or orbitals (Fig. 1). Each electron's energy depends on its quantum state (the orbital it is in) and the number of positively charged protons in the atom's nucleus. Electrons with low principal quantum numbers (those close to the nucleus) are tightly bound; they require large amounts of energy to remove them (i.e., to cause ionization). Electrons with higher principal quantum numbers (those farther from the nucleus) are less tightly bound; less energy is required to remove them. Atoms with many positive protons in the nucleus (elements of high atomic number) tend to bind their inner shell electrons more tightly. Atoms with few protons in the nucleus (elements of lower atomic number) are more easily stripped of their inner shell electrons.

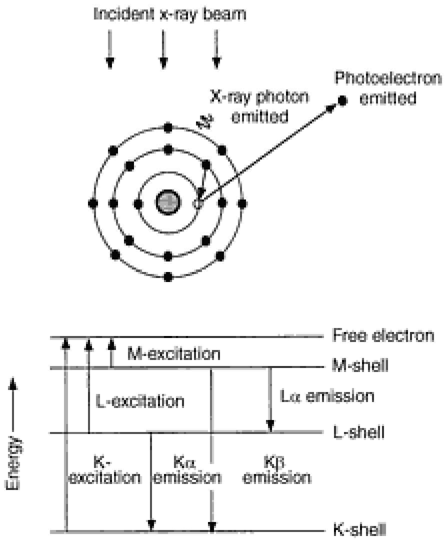


Fig. 1 Excitation of atom in sample by ejection of electrons (photoelectron production), and relaxation of excited atom by electronic transitions and accompanying characteristic x-ray emission

The net result is that each element has a unique set of known electron energy levels. Similarly, the set of energy differences between these electron energy levels is also unique for each element and constitutes a characteristic "fingerprint" by which each element can be identified. In XRF spectroscopy (as well as many other analytical methods), the combined electron energy level "fingerprints" of the elements present in the sample are experimentally obtained and are then compared to the "fingerprints" of known elements. From these comparisons, it is possible to identify the elements and their compositions present in a sample.

When sufficient energy is externally supplied to a sample (of unknown composition), some of the electrons are excited to higher quantum states (energy levels) or removed from the atom (ionization). These "excited" atoms quickly "relax" by electrons from higher energy levels filling the vacated levels. When this happens, photons are emitted whose energies are equal to the differences between the two energy levels involved; this process is called fluorescence. If the energies of these emitted photons are measured, they provide the "fingerprint" of the unknown sample. This measurement can then be compared to the known "fingerprints" of the elements, enabling determination of which elements are present in the sample and the concentration of each element present. Which elements are present can be deduced from the energies of the photons emitted by the sample. How much of each element is present can be deduced from the numbers of photons with energies characteristic of the various elements.

The characteristic energies emitted as excited atoms relax span a range of the electromagnetic spectrum. Electronic transitions between inner shells typically produce x-rays (photons with energies in the 200 to 20,000 eV range, characterized by wavelengths of 6 to 0.06 nm).

Instrumentation. A simplified schematic of an XRF spectrometer is shown in Fig. 2. A beam of x-rays is produced by electronic excitation of a metal target in the instrument's x-ray source. The beam's only function is to excite atoms in the sample. As the incident x-ray beam is directed onto the sample surface, it penetrates some small distance into the sample, typically 10 to 100 μm, depending on the atomic numbers of the elements in the sample. Penetration depths are greater for low atomic number elements. The incident x-rays excite atoms in the sample, transitioning some of their inner shell electrons to higher energy levels. As the excited atoms relax, x-ray photons are emitted corresponding to the differences in the characteristic energy levels of the elements in the sample.

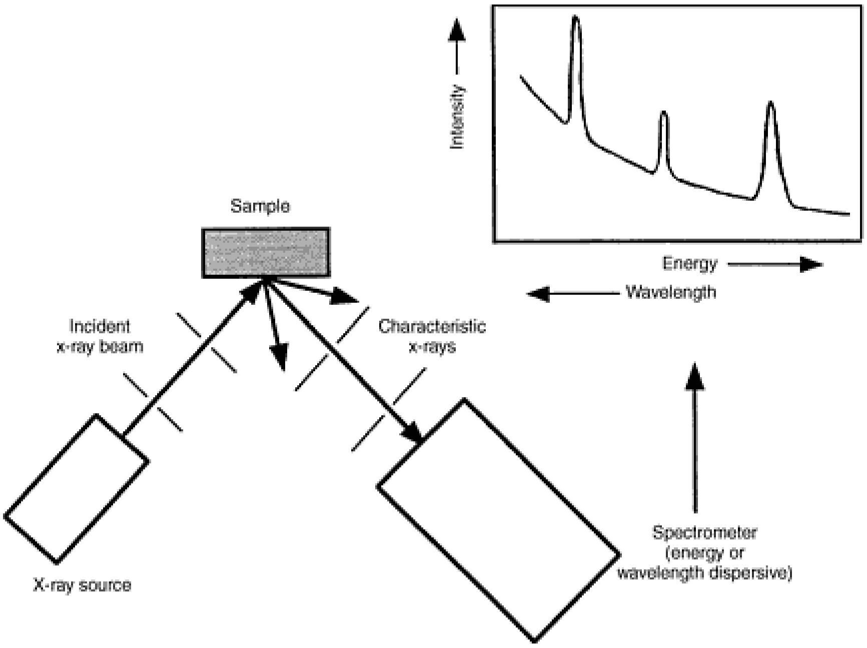


Fig. 2 Schematic of x-ray fluorescence spectrometer. X-rays emitted from the sample are analyzed to determine the characteristic energies (or wavelengths) of x-rays emitted and the intensities of the various characteristic energies

Qualitative analysis (determination of which elements are present) is done by comparing the energies of the x-rays emitted from the sample with the known characteristic x-ray spectra of each element (Fig. 3). Quantitative determination of the concentration of each element present is computed based on the intensities of the various characteristic x-ray energies, also shown in Fig. 3. Quantitative analyses can be most accurate by comparing the x-ray intensities from the unknown sample with their counterparts from a series of standard similar and known compositions. All modern instruments are equipped with computers to facilitate this calibration and measurement process. The use of progressively more powerful computer hardware and software has substantially decreased the need for standards with compositions tailored to specific classes of alloys. Many current analyses are done based only on pure element standards, using the computer to make composition-dependent corrections by iterative means.

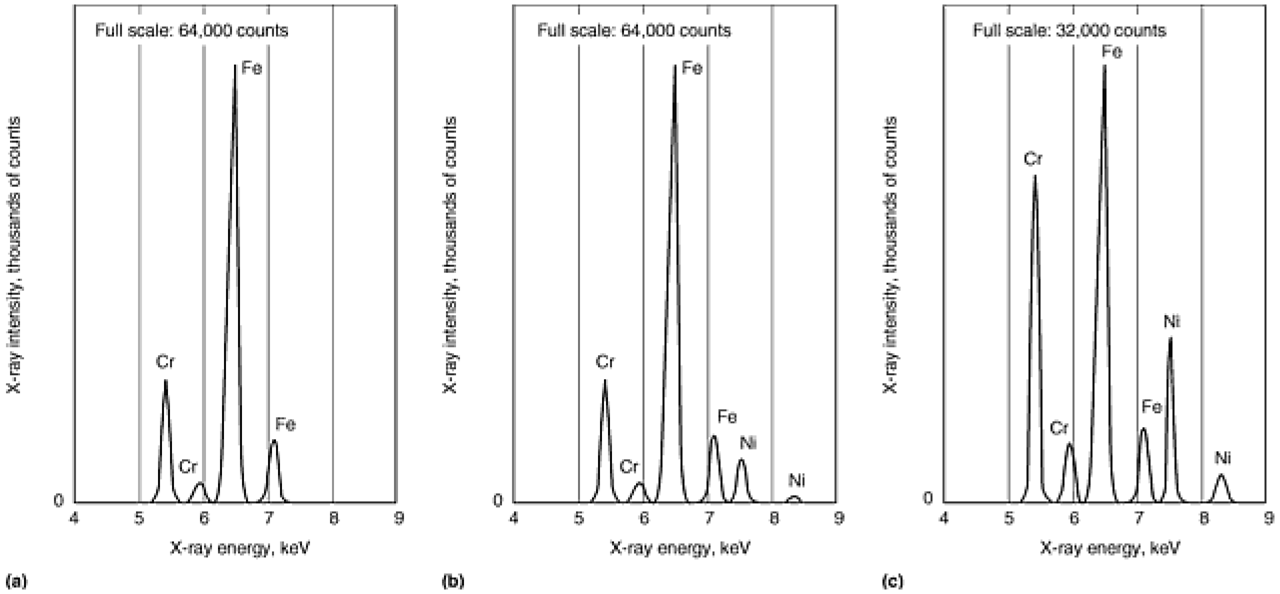


Fig. 3 X-ray fluorescence spectra of (a) Fe-16.4%Cr, (b) Fe-12.3%Cr-12.5%Ni, and (c) Fe-25.7%Cr-20.7%Ni. The iron, chromium, and nickel peaks occur at the same characteristic energies, but the intensities of the peaks increase with concentration. Courtesy of Jim Brangan, Sandia National Laboratories

Due to the dual particle and wave nature of electromagnetic radiation, a simple beam of x-rays can be thought of both as a wave with a characteristic wavelength and a stream of photons each having the same characteristic energy. The photon energy is inversely related to the wavelength by the equation: photon energy = hc/λ, where h = Plank's constant, c = velocity of light, and λ= wavelength.

It is important to distinguish between x-ray energy and x-ray intensity. Energy is defined by the energies of the photons or the wavelength of the beam. Intensity is defined by the number of photons or the amplitude (height) of the wave. Of course, many x-ray beams are made up of numerous energies or wavelengths, not just one as described above.

Wavelength Dispersive versus Energy Dispersive Detectors. The x-rays emitted from the sample in an XRF spectrometer are detected and analyzed in one of two ways: wavelength dispersive or energy dispersive analysis. In wavelength dispersive instruments, the emitted x-ray beam is directed onto one of several crystals that separates it into its component wavelengths by diffraction (Fig. 4). The diffraction principle is described in the article "X-Ray Diffraction for Bulk Structural Analysis." For current purposes, envision it as similar to separating light into its component wavelengths by passing through a prism. An electronic counter is scanned over the angular range of the spectrometer, and a plot constructed of x-ray intensity versus wavelength (wavelength is calculated from the angle and characteristics of the diffracting crystal). Alternatively, the counter can be set to a series of predetermined wavelengths corresponding to the elements in the sample (presuming this is known or has already been determined), and the numbers of x-rays at each of these wavelengths counted for a specific length of time.

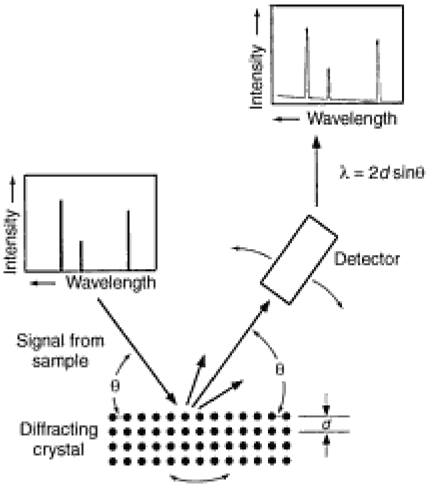

Intensity
Wavelength
λ = 2d sinθ
Intensity
Wavelength
Detector
Signal from sample
θ
θ
Diffracting crystal
d

Fig. 4 Schematic of wavelength dispersive x-ray detector. Detector can mechanically scan a range of angles to produce a plot of intensity vs. wavelength, or it can be set at specific angles corresponding to the characteristic wavelengths of elements known to be in the sample, counting the x-ray intensity at each angle.

In energy dispersive instruments, the emitted x-ray beam is analyzed electronically, photon by photon (Fig. 5). The x-ray beam is directly into a semiconductor device (a lithium-drifted silicon crystal). As each x-ray photon enters the detector crystal, it creates numerous electron-hole pairs as it expends its energy interacting with the atoms in the detector. These electrons and holes are collected and counted at positive and negatively biased sides of the detector. The energy of the photon is determined from the number of electron-hole pairs it creates (proportional to the energy of the photon). The detector electronics sense when each photon enters the detector and require that a photon's energy be analyzed before accepting input from any additional photons. Typically, several thousand photons are analyzed per second. As these energies are measured, a histogram of the numbers of photons counted corresponding to each energy is plotted on a cathode ray tube. The result is a digital plot of intensity versus energy, similar to what is obtained from wavelength dispersive spectrometers (Fig. 6).

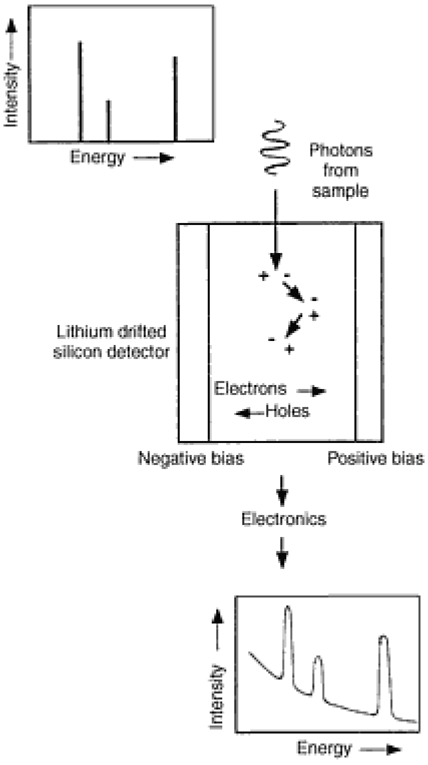

Intensity
Energy
Photons from sample
Lithium drifted silicon detector
Electrons
Holes
Negative bias
Positive bias
Electronics
Intensity
Energy

Fig. 5 Schematic of energy dispersive x-ray detector. Detector measures the energy of each incoming x-ray photon by counting the number of electron-hole pairs it produces. A histogram is then developed and plotted of the x-ray energies of the many (typically tens to hundreds of thousands) photons measured during the counting period.

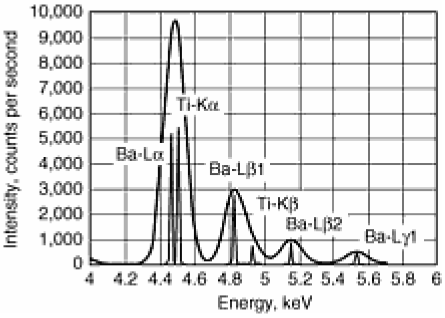


Fig. 6 Superimposed spectra of $BaTiO_3$ obtained from EDS and WDS systems (WDS spectrum replotted on energy scale, rather than wavelength). Note that the WDS spectrum has much sharper lines, thus enabling resolution of nearby peaks that overlap one another on EDS spectrum. Note also that the WDS spectrum has less background noise. Source: C. Brundle, C. Evans, and S. Wilson, *Encyclopedia of Materials Characterization,* Butterworth-Heinemann, 1992, p 128

Wavelength dispersive spectrometers (WDS) predate energy dispersive spectrometers (EDS), but each has inherent advantages. The primary advantage of energy dispersive systems is speed. They can collect a complete spectrum with several hundred thousand counts in approximately one minute. However, wavelength dispersive systems have superior energy resolution (this can be important for separating signals from elements whose characteristic emission energies are very close to one another), as well as improved signal-to-noise ratios. As a result, energy dispersive systems are ideally suited for performing routine qualitative analyses, as well as quantitative analyses where speed is more important than the highest possible precision. On the other hand, difficult qualitative analyses and the most precise quantitative analyses can best be performed on the slower wavelength dispersive systems.

Fine Beam Instruments. Some XRF instruments are specifically designed to characterize compositional uniformity and to map compositional variations within a sample. Such instruments typically are capable of collimating the incident x-ray beam to smaller diameters (as low as ~0.1 mm), thus enabling operator-defined adjustment of lateral spatial resolution. In addition, the sample is usually mounted on an *x-y* stage that automatically translates it to the successive measurement points. The results of sequential analyses performed over a predefined trace on the sample are presented as a plot of composition versus position. Similarly, the results of many analyses performed over a predefined area are typically presented as a computer-generated color-coded two-dimensional map of composition versus position. This map provides a method for characterizing chemical inhomogeneities on a spatial resolution scale midway between the ~1 cm range of "bulk XRF" and the ~1 μm scale of electron probe microanalysis, for example, characterizing segregation patterns in cross-sectioned ingots.

Capabilities of Related Techniques

Optical Emission Spectroscopy (OES) operates on the same atomic principles but bases its analyses on visible light, rather than x-rays. It has somewhat better sensitivity than XRF and better detection for some light elements, such as carbon. Some combinations of elements that exhibit interferences in the x-ray regime are free of interferences in the visible light regime and can be better analyzed by OES.

Combustion and vacuum fusion analysis is well suited to measuring gaseous impurities in metals.

Electron probe microanalysis (EPMA) operates on the same atomic principle as XRF, but it uses a focused electron beam to excite and generate x-rays in very small portions of the sample. It can thus be used to perform quantitative analyses on features as small as several micrometers and to generate quantitative elemental maps with several micrometer spatial resolutions.

Optical Emission Spectroscopy (OES)

Capabilities

- Detection and quantification of most elements (poor sensitivity for halogens, hydrogen, nitrogen, oxygen, and noble gases).

Typical Uses

- Qualitative and quantitative elemental analyses of major, minor, and trace elements in metals and alloys.

Detection Threshold and Precision

- Threshold sensitivity on the order of tens of parts per million (ppm): 0.001 to 0.01%
- Precision of quantitative analyses: photographic instruments, ~5% relative or 0.05% absolute, whichever is greater; direct reading and charge coupled device (CCD) instruments, ~1% relative or 0.01% absolute, whichever is greater
- Lower threshold sensitivity and greater precision can be achieved with related techniques

Limitations

- Elements such as hydrogen, oxygen, nitrogen, halogens, and noble gases cannot be analyzed quantitatively.
- Carbon and sulfur can only be measured in instruments equipped with vacuum chambers and in cases where the sample has not been powdered and mixed with these elements.
- Some combinations of elements are difficult to determine because of overlapping energies in the visible light region.

Amount of Material Sampled

- *Powders:* ~1 g (entire sample)
- *Bulk solids:* About 5 mm diameter surface spot, sampling depth ~100 μm

Sample Requirements

- *Metal samples* are typically ground to produce a flat uncontaminated surface for analysis. Most direct reading instruments can accommodate solid metal samples 10 cm or more in size. The technique is nondestructive except for the ~5 mm diameter surface blemishes produced by the arc.
- *Nonconductive samples* are typically powdered and then mixed with a conductive low-atomic number material, usually graphite. Samples as small as ~10 μg of powder (conductive or non-conductive) can be analyzed in this way.

Operating Principles

Physical Basis. Optical emission spectroscopy operates on the same atomic principles as XRF spectroscopy, except that analyses are based on visible light, rather than x-rays. Visible light is produced by transitions between electrons in outer-shells (far from the nucleus), while x-rays are produced by inner-shell transitions. Photons of visible light have much lower energies than x-rays (1.5 to 4 electron volts for visible light, compared to 200 to 20,000 electron volts for x-rays), and correspondingly much longer wavelengths (~800 to ~300 nm for visible light, compared to 6 to 0.06 nm for x-rays).

The energies of the outer shell electrons on which OES is based can be substantially influenced by the surrounding atoms to which they are bonded in solid samples. As a result, these bonds need to be completely broken for OES spectra to appropriately reflect the energies of the elements present in the sample. This break occurs by supplying sufficient energy to vaporize and decompose a portion of the sample into its component atoms, as well as to excite the atoms in this plasma.

Instrumentation. The external energy is frequently supplied by striking an electrical arc to the surface of the solid sample (Fig. 7). The arc vaporizes a small portion of the sample and ionizes the atoms, producing a plasma. Photons are emitted corresponding to the differences in the characteristic energy levels of the elements in the plasma. The visible light portion is analyzed by passing it through a grating to separate it into its various component wavelengths (similar to separating white light into its component wavelengths by passing it through a glass prism). The resulting spectrum is recorded and compared to the spectra of known elements to determine what elements are present. The concentrations of each element present are deduced from the intensities (numbers of photons) corresponding to each characteristic wavelength. Quantitative determination of the concentration of each element present is done by comparing the intensities from the unknown sample with their counterparts from a series of standards of known concentration.

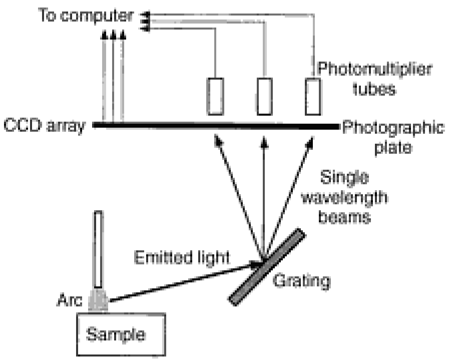


Fig. 7 Schematic of optical emission spectrometer. Light emitted from the vaporized and excited portion of the sample are analyzed to determine the characteristic wavelengths of light emitted and the intensities of the various characteristic wavelengths.

Photographic Instruments. Two methods have historically been used for recording the spectra and analyzing the data, but both of these are currently being replaced by a third method based on newer technology. In photographic emission spectroscopy, the various emitted wavelengths and intensities coming from the grating are directly recorded on a photographic plate. The elements present and their concentrations are deduced by direct visual comparison of the spectrum from the sample and spectra from standards of known composition. This process can be made more quantitative by using a densitometer to read the plates and compare the spectra. Photographic optical emission spectroscopy is readily used for both qualitative and quantitative analysis. Major and minor alloying additions can be readily detected and quantified. Trace elements can typically be detected and quantified down to the 10 to 100 ppm (parts per million) range.

Direct Reading Instruments. Direct reading emission spectrometers have more often been used in cases where particular combinations of elements must be routinely and frequently quantified, such as in measuring the compositions of heats being produced by an aluminum ingot production facility. In these instruments, photomultiplier tubes are set up at the wavelength positions corresponding to each element of interest. These tubes measure the intensities of light obtained from the sample at each predetermined characteristic wavelength and input the results to a computer. The computer then compares these intensities to the corresponding intensities from various standards of known composition (which are already stored in its memory) and calculates the composition of the sample in a matter of seconds. This facilitates rapid quantitative analysis of samples of unknown but similar composition. Because they are only set up to analyze for specific preselected elements and over commonly encountered composition ranges, direct reading emission spectrometers are not useful for qualitative or quantitative analysis of broader ranges of samples.

Instruments with CCD Detectors. Both of the previously described methods of detection are now being supplanted by CCD detectors (a high-resolution array of solid state light detectors). These detectors take the place of photographic plates and electronically record both the location (wavelength) and intensity (brightness) of the light emitted from the sample. The output of the CCD detector is input to a computer, which constructs a histogram of intensity versus wavelength. The computer also facilitates comparison of the observed wavelengths with the known characteristic wavelengths of each element, thus providing for qualitative determination of which elements are present in the sample. In addition, the computer can make quantitative determinations of the concentrations of each element present from the intensities of the emitted light at various characteristic energies. These determinations can be made based on comparison with calibrated standards (measured by the instrument and stored in the computer memory) or based on pure element standards. Analyses based on calibrated standards are typically used in cases where greater accuracy and precision are required. In essence, then, an instrument equipped with a CCD detector is like a direct reading instrument with a semi-infinite number of detectors positioned at every wavelength of possible interest, which provides a rapid and powerful capability for both qualitative and quantitative analysis.

Capabilities of Related Techniques

Inductively coupled plasma atomic emission spectroscopy (ICP/AES) operates on the same atomic principle. However, solid samples are dissolved into liquid solutions that are then aspirated into an argon plasma. This process provides greater flexibility, as liquid standards can be made of essentially any combination of elements, including combinations that cannot be obtained in solid form. ICP can be used for both qualitative and quantitative elemental analysis. Its detection limits are lower than those of other OES methods; however, because the solid sample must be dissolved (and diluted) in a liquid, the effective detection limits for analyzing solid samples are similar.

Inductively Coupled Plasma Mass Spectroscopy (ICP/MS). This combined technique provides better detection limits for trace elements, in some cases down to the parts per trillion range. The dissolved sample is aspirated into the plasma and ionized. Ions from the plasma are then input to a mass spectrometer that determines which elements are present in the plasma. The increased sensitivity of the mass spectrometer provides for lower detection limits, typically in the parts per billion range.

Atomic absorption spectroscopy (AAS) operates on the same atomic principle as OES, but it measures the intensity of light absorbed by the liquid sample aspirated into a flame or graphite furnace, rather than the light emitted. Flame AAS has similar sensitivity to OES. Graphite furnace AAS exhibits better sensitivity for trace elements, similar to ICP/MS, but is simpler and less expensive to set up and operate. Only one element can be measured at a time because single wavelength light sources are used for each element, which makes AAS inappropriate for qualitative analysis.

X-ray fluorescence spectroscopy (XRF) operates on similar physical principles to OES, but it excites the sample using x-rays rather than thermal energy and analyzes the x-rays emitted from the sample rather than the visible light. XRF is completely nondestructive and can be used for both qualitative and quantitative analysis. It provides a good complement to OES, because the interferences (overlapping energies) in the x-ray regime are different from those in the visible light regime. It is not as sensitive as OES for analyzing trace elements. Detection limits are typically in the 100 to 1000 ppm range.

Combustion and Inert Gas Fusion Analysis

Capabilities

- Detection and quantification of carbon, sulfur, and dissolved gases

Typical Uses

- Quantitative analysis of the amounts of carbon, sulfur, and dissolved gases in metals

Detection Threshold and Precision

- Threshold sensitivity: In the vicinity of 50 ppm (0.005%) for sulfur, 10 ppm (0.001%) for carbon, 1 ppm for oxygen, nitrogen, and hydrogen
- Precision of quantitative analyses: sulfur, ~20% relative or 0.005% absolute, whichever is greater; carbon, ~5% relative or 0.001% absolute, whichever is greater; oxygen, nitrogen, and hydrogen, ~5% relative or 0.0001% absolute, whichever is greater

Amount of Material Sampled

- Entire sample (typically ~1 g)

Limitations

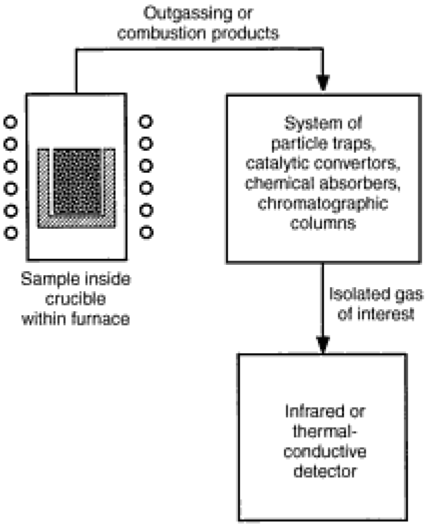
- Samples containing highly stable nitrides or oxides require special treatment.
- Metals with low boiling points require special treatment.

Sample Requirements

- Solid samples in the range of 0.1 g to several grams are usually machined to fit into the sample cups of the instrument. It is desirable to use regular shapes with small ratios of surface area to volume in order to minimize the contributions of surface adsorbed gases to the results.
- Samples should be cleaned immediately prior to analysis.
- These methods destroy the sample.

Operating Principles

A schematic diagram of the similar high-temperature combustion and inert gas fusion processes is shown in Fig. 8. Small samples of known weight are heated to very high temperatures. The elements of interest are driven off as either elemental gas or gaseous oxidation products. These gaseous products are then separated and detected, permitting quantification of their concentrations in the original samples.



Outgassing or combustion products
System of particle traps, catalytic convertors, chemical absorbers, chromatographic columns
Sample inside crucible within furnace
Isolated gas of interest
Infrared or thermal-conductive detector

Fig. 8 Schematic of combustion/inert gas fusion apparatus

For many years, the LECO Corporation has been a primary manufacturer of equipment for high-temperature combustion and inert gas fusion analysis. As a result, these analyses are frequently lumped together and referred to as "LECO" analyses. The use of this common term in this article should not be taken as an endorsement of LECO Corporation instruments or as an indication that other sources of similar equipment are not available.

In the case of combustion analysis for carbon or sulfur, the sample is induction or resistance heated to ~1400 °C (2550 °F) in oxygen, which causes the sample to be completely oxidized. The metal oxides are left as solid, but the carbon and sulfur form CO, CO_2, and SO_2, which are liberated as gases. These gases are then passed through a series of traps, absorbers, and converters to separate them and remove interfering elements. They are then quantified using detectors based on either thermal conductivity or absorption of infrared light.

In the case of inert gas fusion for oxygen, nitrogen, or hydrogen, the sample is heated by either induction or by passing a high current through it to ~3000 °C (5450 °F) in an inert gas. The dissolved gases are driven off at this extremely high temperature. In some cases, these gases combine with other elements in the system; for example, oxygen reacts with carbon to form CO or CO_2. The liberated gases and/or reaction products are then passed through a series of particle traps, catalytic converters, gas chemical absorbers, and chromatographic columns to separate and purify them. They are then quantified using detectors based on either thermal conductivity or absorption of infrared light, as in combustion analysis.

Capabilities of Related Techniques

X-ray fluorescence spectroscopy (XRF) can analyze nondestructively for carbon and sulfur but with higher detection limits and reduced precision.

Optical emission spectroscopy (OES) can analyze less destructively for carbon and sulfur, but with higher detection limits and reduced precision.

Hot extraction high vacuum analysis is similar to inert gas fusion, but gases are liberated at lower temperatures (without destroying sample). Gas evolution can be monitored as a function of time or temperature, thus permitting separation of internally dissolved and surface adsorbed gases.

X-Ray Diffraction for Bulk Structural Analysis

Introduction

X-RAY DIFFRACTION (XRD) is the most extensively used method for identifying and characterizing various aspects of metals related to the arrangements and spacings of their atoms. XRD techniques are equally applicable to other crystalline materials, such as ceramics, geologic materials, and most inorganic chemical compounds.

Overview of X-Ray Diffraction

Capabilities

- Determination of crystal structure, lattice parameters, and interplanar spacings in crystalline materials
- Characterization of defect densities and crystallite sizes
- Characterization of preferred crystallographic orientations in polycrystalline samples
- Determination of orientations of single crystals

Typical Uses

- Identification of phases or compounds present in metals, ceramics, corrosion products, etc.
- Quantitative determination of fractions of each phase in multi-phase mixtures, such as retained austenite in steel
- Determination of lattice parameters and changes in lattice parameters due to alloying and temperature effects
- Measurement of residual stresses
- Characterization of crystallite size and perfection
- Detection of order and disorder transformations
- Characterization of preferred orientations, such as rolling textures in sheet
- Determination of single crystal orientations
- Determination of crystal structure and lattice parameters of new compounds (not described in this article)

Operating Principles

Physical Basis. When an x-ray beam is directed onto a crystalline sample, a number of additional nonparallel beams emerge from the sample. The angles at which these beams emerge and their relative intensities provide information about the lattice geometry, orientations, and arrangements of atoms in the crystal(s) that make up the sample.

The incoming or incident x-ray beam consists of electromagnetic radiation, an electric field traveling at the speed of light whose strength varies sinusoidally with time at any point in the beam. When an x-ray beam is directed onto a metal sample, it penetrates some distance into the sample, typically 10 to 100 μm, depending on the atomic numbers of the elements in the sample. Penetration depth increases with decreasing atomic number. As it penetrates, the beam interacts with the electrons associated with the atoms that make up the sample. A small fraction of these electrons are excited to higher energy states, as described in the section "X-Ray Fluorescence Spectroscopy" in the article "Bulk Elemental Analysis."

Most electrons remain unexcited but are set into oscillatory motion around their centers by the sinusoidally varying electric field of the incident beam. Each oscillating electron, in turn, emits electromagnetic radiation of the same wavelength as the incident beam. This emitted radiation goes out radially from the electron over the entire 360° solid angle. In effect, each electron acts as an x-ray scattering center, sending out concentric waves of x-rays with wavelengths equal to that of the incident beam (Fig. 1).

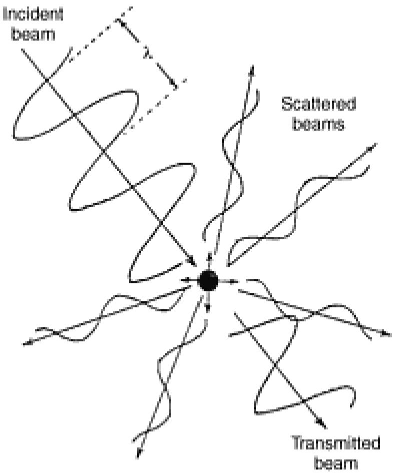


Fig. 1 Electron scattering of x-rays. Each electron acts as a scattering center, sending out in all directions x-rays with the same wavelength as the incident beam.

By summing the contributions of the scattered beams from all of the electrons, it is possible to predict the angular distribution of the x-rays emitted from the sample. The mathematics of this summing process is not as overwhelming as it might first appear. Because the electrons are associated with atoms, each atom can be considered to be the net scattering center corresponding to all of its electrons. The additional fact that the atoms are crystallographically arranged in a three-dimensional periodic array makes the summing problem mathematically tractable. The net result is that constructive interference occurs and results in a strong diffracted beam. However, this reaction occurs only when the following equation, known as Bragg's law, is satisfied: $n\lambda = 2d \sin\theta$, where n = any integer, λ= wavelength of incident and diffracted beams, d = spacing of adjacent diffracting planes in the crystalline sample, and θ= angle between incident beam and diffracting plane, as well as between the diffracting plane and the diffracted beam.

Bragg's law can be understood in terms of Fig. 2. Consider atom A in plane I and atom B in the adjacent plane II. Geometric construction shows that the difference in total path length is equal to $2d \sin\theta$. The exiting beams, A and B, will constructively interfere with one another when they are 360° out of phase with one another, or when λ, the wavelength of the incident and diffracted beams, is equal to the pathlength difference. Constructive interference will also occur if beams A and B are 720° or any multiple of 360° out of phase; hence, the general condition for constructive interference is Bragg's law, as given above.

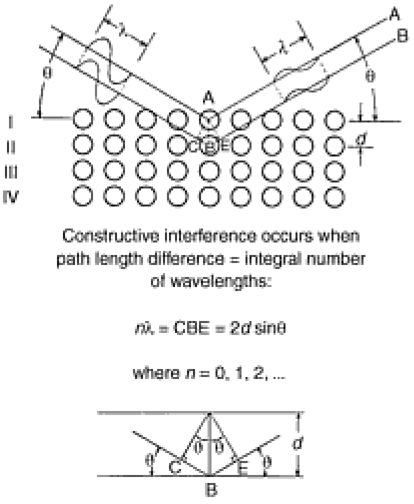

λ
λ
A
B
θ
θ
A
I
II
III
IV
C
B
E
d
Constructive interference occurs when path length difference = integral number of wavelengths:
nλ = CBE = 2d sinθ
where n = 0, 1, 2, ...
θ
θ
θ
θ
C
E
d
B

Fig. 2 Bragg's law, which defines the conditions for constructive interference and the angles at which diffracted beams of x-rays will be emitted from a crystalline assembly of atoms

The simple two-plane summation (Fig. 2) predicts perfectly constructive interference (maximum net diffracted intensity) at angles that result in beams A and B being 360° out of phase with one another. Similarly, perfectly destructive interference (zero net diffracted intensity) at angles result in beams A and B being 180° out of phase with one another. At other intermediate angles, beams A and B would be neither completely in phase nor out of phase with one another. So it would seem that partial constructive interference would occur, resulting in a diffracted beam intensity that varied continuously with the angle. In reality, however, this summation must be done over hundred or thousands of adjacent planes, not just two. When additional planes are included in the summing process, the outcome is virtually complete destructive interference (zero diffracted intensity) at all angles except those that satisfy Bragg's law.

Figure 2 depicts only the simplest type of atomic planes. In reality, many sets of planes can be defined, each with its own characteristic interplanar spacing, as shown for a simple two-dimensional lattice in Fig. 3. An even greater variety of planes can be defined in a three-dimensional lattice. Each of these sets of planes can give rise to diffraction. As a result, numerous diffracted beams are produced in most XRD analyses, each of these beams being associated with a particular set of planes in the crystalline sample.

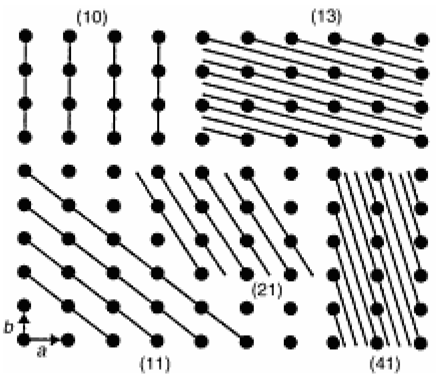


Fig. 3 Various planes of atoms defined in simple two-dimensional "crystals." Each plane is defined by its Miller indices, computed from the reciprocals of its intersections with the *x*- and *y*-axes. Each plane has a characteristic interplanar spacing. Source: Ref 1

Crystal planes are typically identified by Miller indices. The indices of a given plane are defined as the reciprocals of the fractional intercepts that the plane makes with the primary crystallographic axes. Figure 3 shows this principle for the simple case of a two-dimensional lattice. Several low-index planes in three-dimensional lattices are also shown in Fig. 4.

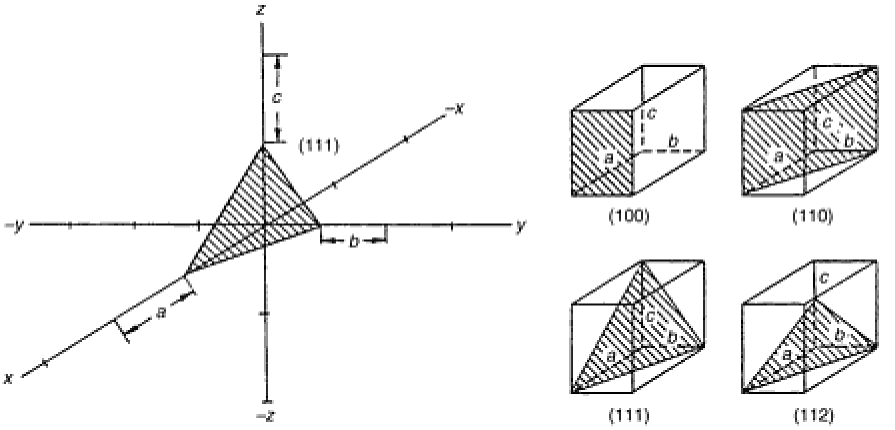


Fig. 4 Planes in three-dimensional crystals defined by their Miller indices. Source: Ref 2

In simple crystal structures (e.g., cubic), planes with various combinations and permutations of the same indices have identical interplanar spacings. These spacings are referred to as types of planes. For example, in a cubic crystal (112), (121), (211), (-112), (-211), etc., all spacings are referred to as planes of the type {112}.

A number of different types of information can be determined from XRD experiments. The primary types of analyses and their uses are described in the following sections, along with information about the threshold sensitivity and precision, limitations, sample requirements, and capabilities of related techniques.

References cited in this section

1. R. Jenkins and R. Snyder, *Introduction to X-Ray Powder Diffractometry,* John Wiley, 1996
2. C. Barrett and T. Massalski, *Structure of Metals,* McGraw-Hill, 1966

Identification of Compounds and Phases Using X-Ray Powder Diffraction

Typical Uses

X-ray powder diffraction is used to identify the crystalline phases present in a sample. Examples of the types of questions that can be answered using x-ray powder diffraction include:

- Is a heat treated steel sample 100% martensite, or does it contain some retained austenite?
- What compounds are present in the corrosion product that formed when an aluminum alloy was exposed to sea spray?
- What compounds are present in the scale formed on a ingot during high-temperature forging?

Solving these types of problems by x-ray powder diffraction is the most common use of XRD in metallurgy.

Experimental Approach

In x-ray powder diffraction, an x-ray beam of a single known wavelength is used to determine the interplanar spacings of the planes in the sample. The sample is typical polycrystalline, ideally containing a semi-infinite number of randomly oriented crystals. Bragg's law dictates that each set of crystal planes will diffract at its own characteristic θangle. Once these θangles at which diffraction occurs have been experimentally determined, the interplanar spacings corresponding to each of them can then be calculated by substituting these angles and the known wavelength of radiation used into Bragg's law. The resulting set of interplanar spacings provides a "fingerprint" of the sample that can be compared to the "interplanar spacing fingerprints" of over 100,000 known compounds, thus permitting identification of the compound(s) present in the sample.

The results of a typical x-ray powder diffraction analysis are shown in Fig. 5. The plot of diffracted intensity versus diffraction angle exhibits a number of peaks, each corresponding to a particular set of crystallographic planes and its characteristic *d*-spacing. The most important information is the angle at which diffraction occurs. The relative intensities of the peaks are determined by a number of factors beyond the scope of this article. Suffice it to say that, for a sample made up of randomly oriented crystals of a given metal or compound, the relative intensities of the various diffraction peaks are predictable and reproducible within a few percent. However, these intensities are of secondary importance in solving the powder diffraction pattern.

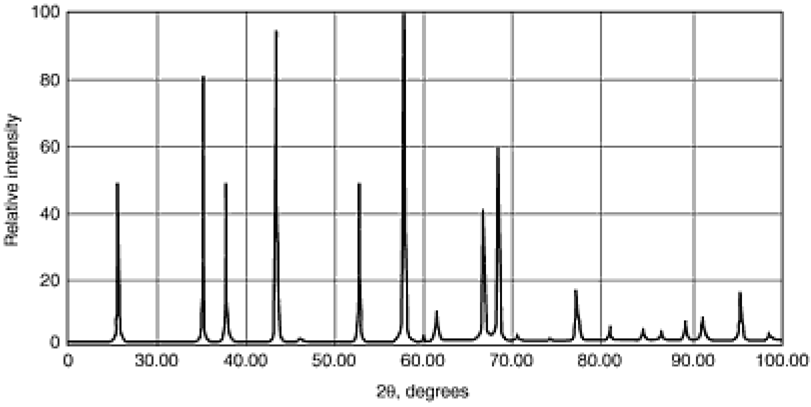


Fig. 5 X-ray powder pattern of Al_2O_3. Source: Ref 1

The pattern can also be summarized as a table of *d*-spacings (each corresponding to a θ angle) and corresponding intensities, typically expressed as a percentage of the most intense peak, as shown in Tables 1(a), 1(b), and 1(c).

Table 1(a) Identification of powder diffraction pattern from Al_2O_3 using the Hanawalt search method

The diffracting angles and intensities (area under each peak) are measured from the unknown sample (in this example from the diffractometer trace in Fig. 5). *d*-spacings are then calculated for each diffraction peak using Bragg's law and the known wavelength of radiation used (in this case, Cu Kα, λ= 1.54178 Å).

2θ, degrees	Intensity, 0 to 100	*d*, Å	Miller indices
25.62	67	3.477	012
35.20	89	2.549	104
37.78	35	2.381	110
41.70	1	2.166	006
43.43	100	2.084	113
46.20	1	1.965	202
52.60	45	1.740	024
57.55	100	1.601	116
59.82	4	1.546	211
61.30	12	1.512	122, 018
66.60	40	1.404	214
68.28	53	1.374	300
70.40	2	1.337	125
74.30	2	1.277	208
77.15	22	1.236	1010, 119
80.80	8	1.189	220
84.50	6	1.146	223
86.50	8	1.125	312, 128
89.08	10	1.099	0210
91.00	12	1.081	0012, 134

95.34	18	1.043	226
98.50	1	1.018	042

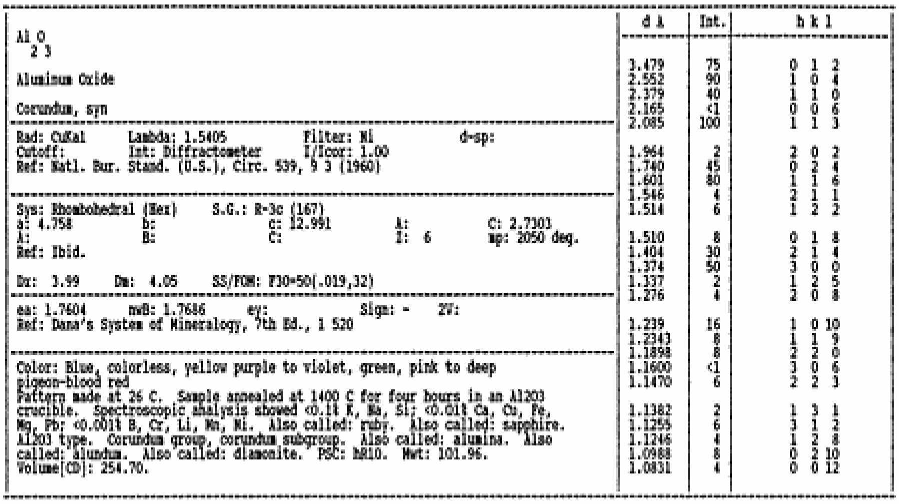
Table 1(b) Hanawalt search method

The *d*-spacings corresponding to the most intense peaks from the sample are then compared with a database of known compounds ordered by the *d*-spacings of their most intense peaks, resulting in a tentative identification of the sample. A set of 25 compounds with similar intense peaks is shown below. Note that the 8 most intense peaks for Al_2O_3 correspond to intense peaks from the sample pattern given in Table 1(a).

2.12_g	**2.55_g**	**4.89_g**	**1.50_g**	**1.63_g**	**1.10_x**	**1.43_x**	**2.99_9**	**cF56**	**$Li_{0.75}Mn_{0.25}Ti_2O_4$**	**40-406**
2.12_8	2.55_x	1.98_x	1.27_x	1.24_8	3.15_5	1.34_5	1.19_5	tP10	FeW_2B_2	21-437
2.11_x	2.55_5	2.79_3	1.37_1	1.09_1	1.98_1	1.51_1	1.16_1	cF*	$Ce_{0.78}Cu_{8.76}In_{3.88}$	43-1269
2.11_8	2.55_x	2.44_x	2.29_7	1.50_7	1.34_7	7.31_5	3.20_5	hP22	K_6MgO_4	27-410
2.10_x	2.55_7	2.61_4	1.45_4	1.29_4	1.80_3	3.88_2	2.49_2	tI10	Pd_2PrSi_2	32-721
2.10_x	2.55_x	2.43_5	1.39_2	0.85_2	3.71_1	1.50_1	1.17_1	hP8	$PmCl_3$	33-1085
2.09_8	2.55_x	6.31_8	1.68_8	3.16_6	2.79_6	1.61_6	1.56_6		$K_{0.72}In_{0.72}Sn_{0.28}O_2$	34-711
2.09_8	2.55_x	2.63_8	1.65_8	1.79_7	2.66_6	1.88_6	3.05_5	mC18.80	$IrB_{1.35}$	17-371
2.09_x	2.55_9	1.60_8	3.48_8	1.37_5	1.74_5	2.38_4	1.40_3	hR10	Al_2O_3	10-173
2.09_x	2.55_x	1.60_x	3.48_7	1.37_6	1.74_5	2.38_4	1.40_4	hR10	Al_2O_3	43-1484
2.08_x	2.55_8	3.22_8	1.57_6	2.00_4	1.61_4	1.75_3	2.40_2	hP6	$EuAl_2EuSi_2$	45-1237
2.08_x	2.55_8	2.16_8	1.18_x	1.17_x	2.02_8	1.16_8	2.33_6	oC20	Cr_2VC_2	19-334
2.08_8	2.55_x	2.14_4	1.23_x	1.32_8	1.17_8	1.30_6	1.64_4	oC8	HfPt	19-537
2.16_x	2.54_6	2.74_5	2.19_4	2.51_4	1.38_2	1.27_2	1.50_1	hR12	$ErFe_3$	43-1373
2.16_x	2.54_x	2.33_x	2.12_x	1.42_9	1.54_8	1.38_8	1.32_8	hP12	Cr_2Hf	15-92
2.16_x	2.54_7	1.38_2	4.14_2	1.46_2	1.27_2	2.07_1	0.93_1	cF24	Co_2Ho	29-481
2.16_x	2.54_6	1.38_2	2.07_2	1.27_2	1.46_2	4.14_1	0.93_1	cF24	$TbNi_2$	38-1472
2.14_x	2.54_8	2.35_8	1.36_7	2.16_6	0.85_6	1.86_6	0.88_5	oP8	TiB	5-700
2.12_x	2.54_x	2.33_x	2.16_x	1.42_9	1.54_8	1.38_8	1.32_8	hP12	Cr_2Hf	15-92
2.11_x	2.54_7	1.49_6	4.87_6	0.86_3	1.62_2	0.94_1	1.22_1	cF*	$AlVO_3$	25-27
2.10_x	2.54_7	2.07_6	1.16_8	1.08_8	1.36_7	1.09_7	1.07_7	cF112	$RbZn_{13}$	27-566
2.10_8	2.54_x	1.57_x	1.21_x	1.72_8	1.68_8	1.51_8	1.45_8	tP5	LuB_2C_2	27-301
2.10_x	2.54_x	1.49_7	4.86_6	1.62_4	2.97_2	2.43_2	1.40_1	cF*	$Mg_{1.5}VO_4$	19-778
2.09_9	2.54_x	3.49_8	6.39_7	3.69_5	2.76_4	2.13_4	1.38_3	hP8	$SmCl_3$	12-789
2.09_x	2.54_x	2.59_8	1.28_8	3.85_5	2.46_5	1.63_5	1.60_5	tI10	$LaPd_2P_2$	37-994

Table 1(c) Hanawalt search method

A card containing all of the information for the tentatively identified compound is compared with the diffraction information from the sample. The card for Al_2O_3 is shown below. Note that all of the diffraction peaks in the sample pattern can be accounted for by Al_2O_3. If unidentified lines were present, it would indicate either that the tentative identification was incorrect, or that one or more additional compounds were present in the sample along with Al_2O_3. The information on the card enables identification of the Miller indices of the planes associated with each diffraction peak, shown in the last column of Table 1(b).



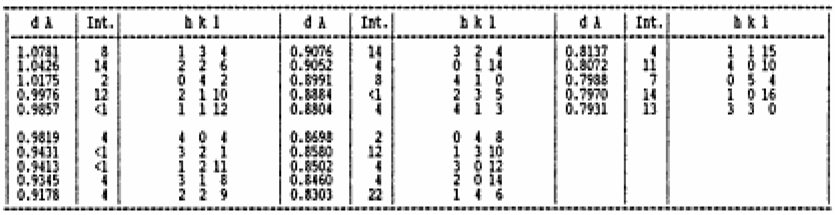
```
Al O
  2 3

Aluminum Oxide

Corundum, syn
-------------------------------------------------------------------------------
Rad: CuKa1      Lambda: 1.5405          Filter: Ni            d-sp:
Cutoff:         Int: Diffractometer     I/Icor: 1.00
Ref: Natl. Bur. Stand. (U.S.), Circ. 539, 9 3 (1960)
-------------------------------------------------------------------------------
Sys: Rhombohedral (Hex)    S.G.: R-3c (167)
a: 4.758        b:               c: 12.991        A:           C: 2.7303
A:              B:               C:               Z:  6        mp: 2050 deg.
Ref: Ibid.

Dx:  3.99     Dm:  4.05     SS/FOM: F30=50(.019,32)
-------------------------------------------------------------------------------
ea: 1.7604      nwB: 1.7686     ey:              Sign: -    2V:
Ref: Dana's System of Mineralogy, 7th Ed., 1 520
-------------------------------------------------------------------------------
Color: Blue, colorless, yellow purple to violet, green, pink to deep
pigeon-blood red
Pattern made at 26 C.  Sample annealed at 1400 C for four hours in an Al2O3
crucible.  Spectroscopic analysis showed <0.1% K, Na, Si; <0.01% Ca, Cu, Fe,
Mg, Pb; <0.001% B, Cr, Li, Mn, Ni.  Also called: ruby.  Also called: sapphire.
Al2O3 type.  Corundum group, corundum subgroup.  Also called: alumina.  Also
called: alundum.  Also called: diamonite.  PSC: hR10.  Mwt: 101.96.
Volume[CD]: 254.70.
```

d A	Int.	h k l
3.479	75	0 1 2
2.552	90	1 0 4
2.379	40	1 1 0
2.165	<1	0 0 6
2.085	100	1 1 3
1.964	2	2 0 2
1.740	45	0 2 4
1.601	80	1 1 6
1.546	4	2 1 1
1.514	6	1 2 2
1.510	8	0 1 8
1.404	30	2 1 4
1.374	50	3 0 0
1.337	2	1 2 5
1.276	4	2 0 8
1.239	16	1 0 10
1.2343	8	1 1 9
1.1898	8	2 2 0
1.1600	<1	3 0 6
1.1470	6	2 2 3
1.1382	2	1 3 1
1.1255	6	3 1 2
1.1246	4	1 2 8
1.0988	8	0 2 10
1.0831	4	0 0 12



d A	Int.	h k l	d A	Int.	h k l	d A	Int.	h k l
1.0781	8	1 3 4	0.9076	14	3 2 4	0.8137	4	1 1 15
1.0426	14	2 2 6	0.9052	4	0 1 14	0.8072	11	4 0 10
1.0175	2	0 4 2	0.8991	8	4 1 0	0.7988	7	0 5 4
0.9976	12	2 1 10	0.8884	<1	2 3 5	0.7970	14	1 0 16
0.9857	<1	1 1 12	0.8804	4	4 1 3	0.7931	13	3 3 0
0.9819	4	4 0 4	0.8698	2	0 4 8			
0.9431	<1	3 2 1	0.8580	12	1 3 10			
0.9413	<1	1 2 11	0.8502	4	3 0 12			
0.9345	4	3 1 8	0.8460	4	2 0 14			
0.9178	4	2 2 9	0.8303	22	1 4 6			

Historically, results such as those presented in Tables 1(a), 1(b), and 1(c) were compared with the ***d***-spacing and intensity fingerprints for ~100,000 known compounds--each tabulated on an index card and organized systematically by the ***d***-spacings of the several most intense peaks. This search and match process is now greatly facilitated by computers that contain all of the information on known compounds in an updatable database. The search is based primarily of the ***d***-spacing information, rather than the intensities, because the assumption that the sample consists of randomly oriented crystals is frequently violated, thus altering the intensities.

Samples Containing Multiple Phases or Compounds

Identification of metals and compounds by x-ray powder diffraction is relatively straightforward when the sample consists of a single phase or compound. When multiple phases or compounds are present, however, the task is more complex, as multiple "fingerprints" are superimposed on one another. Fortunately, software is available to analyze and solve such complex patterns. Solution of complex overlapping patterns can be simplified by providing additional information to the computer regarding what elements are, are not, and may be in the sample. This information is typically obtained by x-ray fluorescence spectroscopy. Once this elemental information has been input, the software searches only compounds that are consistent with it.

Once the phases or compounds present in a multi-phase sample have been identified, the percentages of each phase or compound present can be deduced from the relative intensities of their diffraction peaks. A common metallurgical example is the determination of the amount of retained austenite present in heat treated steels. The most precise analyses are based on comparison of results from the unknown with those from a number of calibrated standards.

Instrumentation

X-ray diffraction analyses have historically been conducted using two types of equipment: the Debye-Scherrer camera and the x-ray diffractometer. The Debye-Scherrer camera is used for powdered samples (Fig. 6). The camera is a light-tight hollow cylinder with a removable cover plate. The powdered sample is placed in a hollow capillary tube at the center of the camera. A strip of photographic film is then placed around its inside perimeter, and the cover plate is applied. The camera is then attached to an x-ray generating tube and the x-rays are directed onto the sample through a collimator. The diffracted x-rays are recorded on the film, which is developed following 1 to 4 h of x-ray exposure (Fig. 7). The θ angles are measured from the film and converted to ***d***-spacings. Intensities are either estimated by eye or quantified using a densitometer.

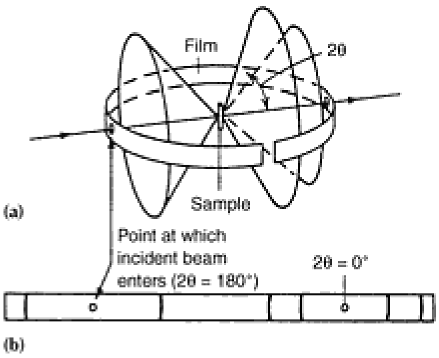

Film
2θ
(a)
Sample
Point at which incident beam enters (2θ = 180°)
2θ = 0°
(b)

Fig. 6 Schematic of Debye-Scherrer powder method. (a) Relationship of film to sample, incident beam, and diffracted beams. (b) Appearance of film when developed and laid flat. Source: Ref 3

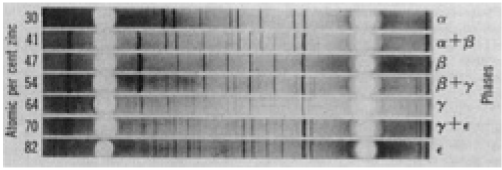

Atomic per cent zinc
30
41
47
54
64
70
82
α
α+β
β
β+γ
γ
γ+ε
ε
Phases

Fig. 7 Debye-Scherrer films identifying phases in copper-zinc alloys of various compositions. Source: Ref 2

The x-ray diffractometer avoids the use of film and is far better suited to automation. The sample is flat, typically either a polished metal surface or a powder adhered to a flat glass slide. The sample is exposed to the incident x-ray beam, and a counter is scanned over the desired range of θ angles (Fig. 8). The result is a plot of diffracted intensity versus diffraction angle (Fig. 5).

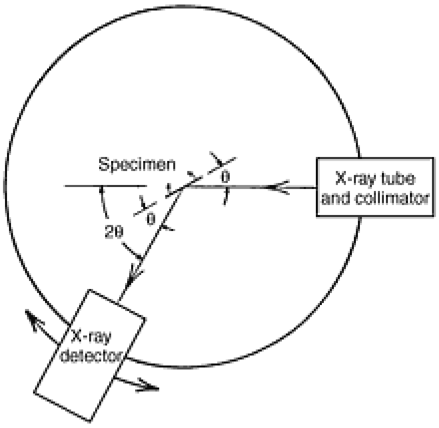

Specimen
θ
θ
2θ
X-ray tube and collimator
X-ray detector

Fig. 8 Schematic of x-ray diffractometer. Typically, the x-ray tube remains stationary while the detector mechanically scans a range of θ angles. The sample also rotates with the detector such that diffraction is recorded from planes parallel to the sample surface.

In recent years, position-sensitive wire detectors and solid state charge coupled device (CCD) detectors (in essence, a high resolution array of solid state light sensors) have permitted all of the diffracted signals to be collected simultaneously, thus overcoming the need to mechanically scan a detector scintillation counter over the range of diffraction angles. This method of collection greatly increases the speed with which diffraction information can be obtained, and it provides a digital electronic format that is amenable to computer-assisted data reduction and analysis.

Detection Threshold and Precision

- Threshold sensitivity: A phase or compound must typically represent 1 to 2% of the sample to be detected
- Precision of interplanar spacing and lattice parameter measurements: ~0.3% relative in routine measurements; within ~0.003% relative in experiments optimized for this purpose
- Precision of quantitative analyses of percentage of individual phases or compounds present in samples containing multiple compounds: 5 to 10% relative or 1 to 2% absolute, whichever is greater (presumes the use of calibrated standards)

Amount of Material Sampled

- Powdered samples: Entire sample
- Polished bulk materials: Typically ~1 cm square area, sampling depth usually in the range 10 to 100 μm (increases with decreasing average atomic number)

Limitations

- Noncrystalline samples produce no diffraction peaks
- Results represent average of many grains or crystals in the sample, not an individual particle. Fine beams (down to ~100 μm diameter) can be used to characterize some individual particles.

Sample Requirements

- *Powders:* 10 mg is typically enough
- *Flat metal samples:* Diffractometers can usually accommodate samples with lateral dimensions up to 5 cm and thicknesses up to 5 mm. Ideally, the surface should be free of deformation in order to get sharp diffraction peaks. Chemical or electropolishing can be used to remove the last vestiges of deformation in mechanically ground and/or polished samples.

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1. R. Jenkins and R. Snyder, *Introduction to X-Ray Powder Diffractometry,* John Wiley, 1996
2. C. Barrett and T. Massalski, *Structure of Metals,* McGraw-Hill, 1966
3. *Materials Characterization,* Vol 10, *ASM Handbook,* ASM International, 1986, p 335

Measurement of Lattice Parameter Changes due to Alloying or Temperature

The addition of alloying elements, heating or cooling, and residual stresses cause slight changes in interplanar spacings, which cause slight shifts in the θ angles at which diffraction occurs. XRD can be used to quantify these changes.

Changes resulting from solid solution alloying can be determined using a diffractometer, as described earlier. Similarly, temperature effects can be characterized using a diffractometer equipped with a furnace to heat the sample to the desired temperature.

The systematic errors inherent in XRD measurements decrease with increasing diffraction angle. As a result, lattice parameter measurements are typically based on information obtained at high diffraction angles. The most precise lattice parameter measurements make use of curve-fitting procedures to extrapolate information to the limiting θ value of 90°.

Precision

- ~0.03% relative with moderate care
- ~0.003% relative with the greatest care

Sample Requirements

- Identical to those indicated above for routine diffractometer examination

Measurement of Residual Stresses

X-ray residual stress measurement is substantially more complex, but its key principles are not difficult to understand. Residual stresses are most often introduced during heat treating or welding and are caused by differential thermal contraction associated with temperature gradients in the material. These stresses cause elastic strains in the material, which manifest themselves as slight departures from the material's normal (unstressed) lattice parameters or interplanar spacings. XRD measurement of these changes in interplanar spacings, then, provides a direct measure of elastic strain, which can be used to calculate residual stress magnitude using the known elastic constants of the material.

Because residual stresses must be calculated from small stress-induced changes in interplanar spacing, it is critical to know precisely the interplanar spacings in an unstressed sample of the material in question. The planes that happen to be parallel to and very close to the free surface provide an internal calibration in this regard, because no stresses can be supported perpendicular to a free surface. The problem then becomes one of comparing the interplanar spacings of planes parallel to the free surface with those inclined at various angles to the surface, and using the pertinent equations of elasticity to calculate from these differences the magnitudes of the stresses in various directions parallel to the surface. From this, the principal in-plane stresses directions can be calculated.

Instrumentation

Residual stresses are typically measured using an x-ray diffractometer equipped with a special specimen holder designed to facilitate measurement of diffraction from planes inclined at various angles to the surface of the sample. (General purpose diffractometers obtain diffraction information only from planes that are parallel to the sample surface. See Fig. 8.) Portable x-ray systems are also frequently used to make field stress measurements on structural components.

Residual stresses vary with position in the component, so measurements are frequently made at numerous locations. The spatial resolution of these measurements is defined by the diameter of the x-ray beam used. The diameter is typically in the vicinity of 1 cm, but it can be as small as 30 μm.

Precision

- ~5% relative or ~5 MPa absolute, whichever is higher (in ideal laboratory conditions)
- Less precise information is obtained when portable x-ray equipment used for residual stress measurement of non-ideal structural components

Limitations

- Because XRD obtains information from the near-surface region of the sample, it only provides surface stress information and is not capable of measuring stresses in the interiors of components.

Capabilities of Related Techniques

Neutron diffraction residual stress measurement is based on the same principles as XRD. Because neutrons penetrate metals to far greater depths, it is possible to measure stresses in the interior or samples, rather than only surface stresses. However, a neutron source is required, so such measurements cannot be made in the field.

Characterization of Crystal Size and Defect Density from Peak Width and Shape

When Bragg's law was discussed earlier, it was noted that the angular range over which significant diffracted intensity is obtained depends on the number of adjacent planes from which diffracted beams are summed. In the extreme case of only two adjacent planes, diffracted intensity would be maximum at the angles satisfying Bragg's law (where perfectly constructive interference occurs). However, it would vary continuously with diffraction angle, only being zero at the angles where perfectly destructive interference occurs, which would result in very broad diffraction peaks. On the other hand, when the beams scattered by a semi-infinite number of adjacent planes are summed, constructive interference and significant diffracted intensity are only obtained at angles that exactly satisfy Bragg's law. In this case, very narrow diffracted beams are obtained. Intermediate between these extremes, the width of diffraction peaks increases with decreasing crystal size. Peak broadening becomes significant as crystal size decreases below ~0.5 μm.

Most cast or wrought metals have sufficiently large grain sizes to justify the assumption that summing occurs over a semi-infinite number of adjacent planes, hence, narrow diffraction peaks are obtained. Phases formed by low-temperature deposition processes and solid state transformations, however, frequently have much finer grains whose sizes can be estimated from the widths of their diffraction peaks (Fig. 9).

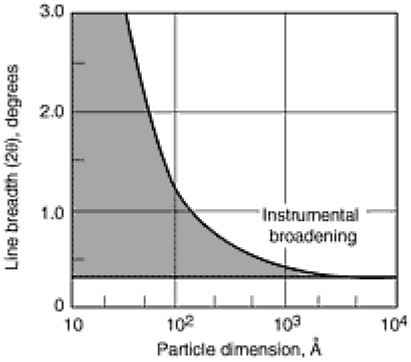

Fig. 9 Effect of crystallite size on peak width. Source: Ref 1

Crystal defects, such as dislocations and stacking faults, also interrupt the long-range periodicity of the crystal lattice, thus resulting in relaxation of the conditions for diffraction and broadening of diffraction peaks (Fig. 10). Analysis of peak width and shape (the details of the intensity versus diffraction angle data) can be used to obtain information on the densities of such defects in the sample.

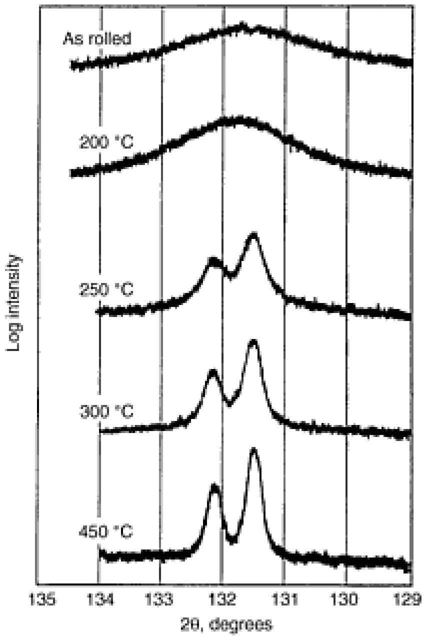

Fig. 10 Effect of dislocations introduced by cold working and removed by annealing on width of diffraction peaks in brass. Source: Ref 1

Peak width and shape measurements are typically made from the output of an x-ray diffractometer. The results of such analyses are useful as semiquantitative indicators of crystallite size and defect density, but typically lack quantitative precision.

Certain alloys exist as random solid solutions (atoms A and B randomly substituting for one another in identical lattice positions) at high temperature, but ordered compounds (atoms A and B arranged in specific nonrandom patterns) at lower temperature (Fig. 11). Such ordering can give rise to additional diffracted beams, thus enabling ordering to be detected and characterized by XRD.

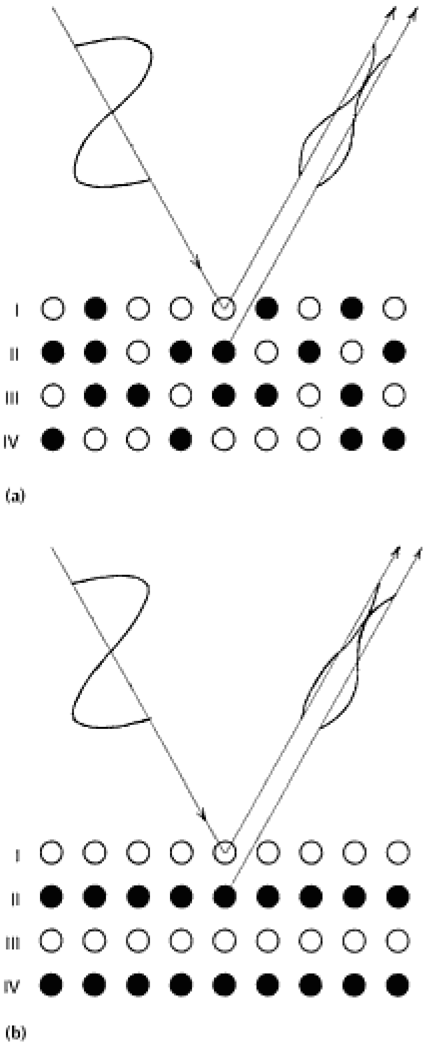

Fig. 11 Principles of diffraction from random and ordered solid solutions. (a) Random solid solution: All planes have equal numbers of A and B atoms, hence equal average scattering power, scattered beams from planes I and II are 180° out of phase and equal in amplitude, so net diffracted intensity is zero. (b) Ordered compound: Adjacent planes are made up entirely of A and B atoms, so they have unequal scattering powers. Scattered beams from planes I and II are 180° out of phase but unequal in amplitude, so net diffracted intensity is not zero (diffracted beam is obtained).

Because x-rays are scattered by their interactions with electrons, atoms of higher atomic number serve as more powerful scattering centers than those with lower atomic numbers. Consider Fig. 11, in which the filled circles represent A atoms of low atomic number and low scattering power, whereas the open circles represent B atoms of high atomic number and higher scattering power.

In a random solution (Fig. 11a), successive planes I, II, III, etc. will all have identical fractions of A and B atoms, so the amplitudes of the x-rays scattered from adjacent planes will be identical. If, as shown in Fig. 11(a), the beams scattered from adjacent planes are 180° out of phase with one another, perfect destructive interference will occur, and no diffracted beam will result.

If ordering occurs so that successive planes have different fractions of A and B atoms, as shown in Fig. 11(b), planes II and IV will have greater scattering power than planes I and III. This increased scattering will result in different amplitudes for the beams scattered from adjacent planes. Because their amplitudes are different, only partial destructive interference will occur between beams that are 180° out of phase with one another. As a result, a diffracted beam will be observed. The presence of extra "superlattice" lines in a diffraction pattern--diffraction at angles where no diffraction occurs for the random solid solution--is indicative of the solution becoming ordered (Fig. 12). Studies of ordering are typically conducted using Debye-Scherrer cameras or diffractometers.

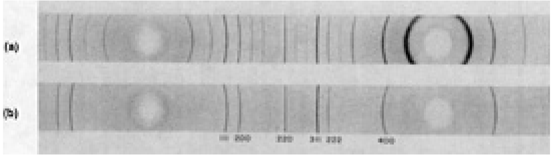

Fig. 12 Debye-Scherrer patterns for ordered and disordered Cu-25Au (at.%). (a) Ordered Cu_3Au compound obtained by slow cooling from 450 °C (840 °F); note extra "superlattice lines" not present in random disordered solid solution. (b) Random solid solution obtained by quenching from 500 °C (930 °F). Source: Ref 4

Limitations

The intensities of these superlattice lines depends on the difference in atomic scattering power between the A and B atoms. In cases where these atoms have greatly different atomic numbers, the amplitudes of the beams scattered from adjacent planes are markedly different, so interference is far from perfectly destructive and the superlattice lines are moderately intense. In cases where the A and B atoms have nearly identical atomic numbers, however, the amplitudes of the beams scattered from adjacent planes are only slightly different. So nearly perfectly destructive interference occurs, and the superlattice lines have such low intensities that they frequently cannot be detected.

Capabilities of Related Techniques

Neutron diffraction can be used to detect and characterize ordering in cases of atoms of similar atomic number. Neutron diffraction is based on the same principles as XRD, but scattering occurs based on nuclear interactions, rather that interactions with electrons. As a result, neutron scattering power does not vary regularly with atomic number, and atoms with similar atomic number frequently have greatly different neutron scattering powers. This provides for more intense neutron diffraction superlattice lines in ordered compounds involving atoms of similar atomic number.

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1. R. Jenkins and R. Snyder, *Introduction to X-Ray Powder Diffractometry,* John Wiley, 1996
4. Taylor, *X-Ray Metallography,* John Wiley, 1961, p 444

Characterization of Preferred Orientations (or Textures)

As noted in the section "Identification of Compounds and Phases Using X-Ray Powder Diffraction," predictable and reproducible intensities are obtained for the diffracted beams corresponding to particular sets of planes in a given material, provided the sample consists of randomly oriented grains. However, there are many causes of nonrandomness in grain orientation. In bulk metals, preferred orientations are frequently caused by metal working operations, such as rolling, forging, or drawing. Thin films deposited by methods, such as electroplating, plasma deposition, and chemical vapor deposition, also tend to grow in particular crystallographic directions. The properties of materials exhibiting preferred orientations tend to be anisotropic. For example, the forming behavior of sheet metal varies depending on the nature and degree of the preferred orientation produced by the previous rolling operations: the degree of working, the temperatures at which it was done, whether the sheet was unidirectionally rolled or cross rolled, etc. XRD provides a means of characterizing such nonrandom orientations or textures.

Instrumentation and Characterization

The simplest way to characterize nonrandom crystallographic orientation is to merely note the degree to which the diffracted intensities from different sets of planes parallel to the surface vary from what would be expected in an ideal sample containing no preferred orientation. For example, a rolled plate in which the diffracted intensity from the {111} planes was 10 times that of a randomly oriented sample would be said to have a {111} texture, or a strong tendency to have the {111} planes aligned parallel to the surface.

A more complete description of preferred orientation can be obtained by doing an x-ray diffractometer experiment in which the incident beam and the detector are set to measure diffraction from a preselected type of plane. A specialized sample holder is used to rotate the sample through a wide range of orientations, and the diffracted intensity is measured as a function of orientation relative to the prior rolling plane and direction. The results are frequently presented in the form of a topologic map on a hemispherical projection, termed a pole figure and shown in Fig. 13. The "contour" lines denote the degree to which the plane of interest tends to be aligned in a particular orientation relative to the prior working axes. Idealized orientations are often then associated with the preferred orientation.

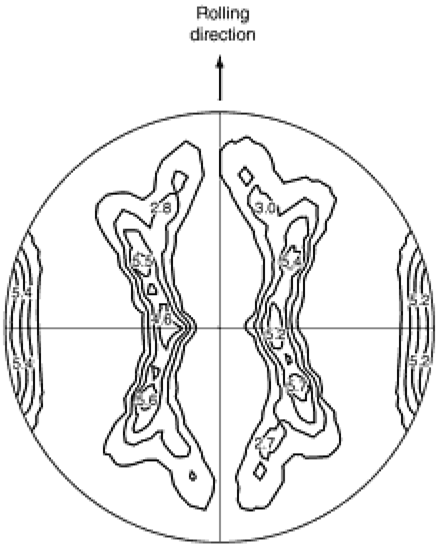

Fig. 13 X-ray pole figure characterizing nonrandom distribution of {111} poles (plane normals) in sample from rolled sheet. Contours indicate pole densities of 1, 2, 3, 4, and 5 times those in a randomly oriented sample. Numbers indicate local maxima. Courtesy of Mike Eatough, Sandia National Laboratories

In recent years, the orientation distribution function (ODF) has been developed to more uniquely characterize the nature of preferred orientations. The ODF is geometrically equivalent to the combined information presented in pole figures corresponding to several different types of planes, but it is superior in that it provides a quantitative analytical description of the probability of particular grain orientations.

Determination of Single Crystal Orientations

The Laue Technique

The Laue technique employs an x-ray beam of continuously varying wavelength to determine the orientation of a single crystal sample of known crystal structure. Referring to Fig. 2, it can be seen that for a stationary single crystal sample in which *d*-spacings and diffraction angles are fixed, the right hand side of Bragg's law has a single completely defined value for each type of plane. If an incident beam with a single x-ray wavelength is used, diffraction only occurs in the fortuitous case where this wavelength (or its multiple) happens to equal one of these values, making both sides of Bragg's law equal. In general, this is not the case, so typically no diffracted beams are obtained. If the incident x-ray beam consists of a continuous range of wavelengths, however, diffraction can occur from each of the set of planes in the crystal (each set of planes "choosing" the wavelength that satisfies Bragg's law). The result is a set of diffracted beams whose arrangement is identical to what would result from a beam of light being reflected from the various types of plane in the crystal.

Instrumentation

The most common experimental arrangement is the back-reflection Laue arrangements shown in Fig. 14. The x-ray beam is directed through a collimator onto the single crystal sample, and diffraction occurs from numerous crystal planes. The sample is usually mounted on a goniometer that permits it to be rotated into the desired orientation based on the results of the Laue experiment. Historically, the diffracted beams have been recorded on a flat piece of photographic film that is developed following the experiment. In recent years, CCD cameras have been replacing film, permitting electronic data collection and computer automated reduction of the diffraction information.

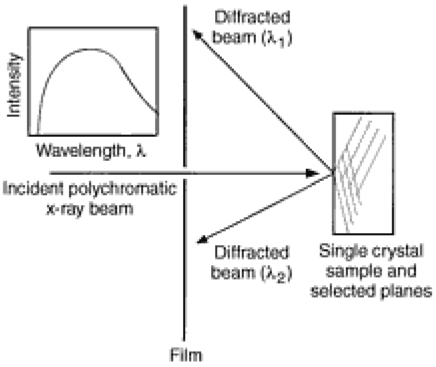
Intensity
Wavelength, λ
Incident polychromatic x-ray beam
Diffracted beam (λ₁)
Diffracted beam (λ₂)
Single crystal sample and selected planes
Film

Fig. 14 Schematic showing back reflection Laue geometry

The symmetry of the resulting pattern is characteristic of the orientation of the crystal, as can be seen in Fig. 15. Comparison of the angular relationships between different spots makes it possible to determine the Miller indices of the planes corresponding to each spot.

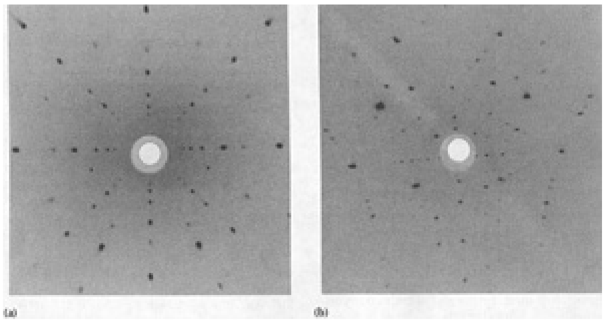

Fig. 15 Back reflection Laue photographs showing (a) low-index high symmetry orientation where the <001> axis of the unit cell (in this case, cubic) is parallel to the beam (normal to the film). Note symmetry about 180° diffraction position at center of film. (b) Higher index orientation (note lower symmetry). Courtesy of Mike Eatough, Sandia National Laboratories

Precision

- Routinely within 0.5 degrees
- Within 0.02 degrees under carefully controlled conditions

References

1. R. Jenkins and R. Snyder, *Introduction to X-Ray Powder Diffractometry,* John Wiley, 1996
2. C. Barrett and T. Massalski, *Structure of Metals,* McGraw-Hill, 1966
3. *Materials Characterization,* Vol 10, *ASM Handbook,* ASM International, 1986, p 335
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Microstructural Analysis

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Introduction

MICROSTRUCTURAL ANALYSIS is the combined characterization of the morphology, elemental composition, and crystallography of microstructural features through the use of a microscope. Light microscopes have been used to characterize the microstructures of metals for over 100 years. The methods and applications of light microscopy are covered in the Section "Metallography" and will not be repeated here. While light microscopy is an important metallurgical tool, it has a number of limitations:

- *Spatial resolution:* Conventional light microscopes cannot resolve features smaller than ~1 μm.
- *Depth of field:* Light microscopes cannot image rough surfaces--samples must be flat in order to be in focus.
- *Type of information provided:* Light microscopes provide images and morphological information, but they do not provide any direct chemical or crystallographic information about the microstructural features observed.

During the past 50 years, however, several types of electron microscopy have been developed and refined to greatly extend our ability to resolve and characterize the morphologies of much smaller microstructural features, to image rough surfaces, and to obtain direct chemical and crystallographic information about microstructural features.

This article reviews the three types of electron microscopies most commonly used in metallurgical studies: scanning electron microscopy, electron probe microanalysis, and transmission electron microscopy.

Scanning Electron Microscopy (SEM)

Capabilities

The scanning electron microscope provides a valuable combination of high resolution imaging, elemental analysis, and recently, crystallographic analysis:

- Imaging of features as small as ~10 nm or less, roughly 100 times smaller than can be seen with light microscopes
- Imaging of rough surfaces
- Qualitative and semi-quantitative elemental analyses on microstructural features as small as ~2 μm
- Identifying crystalline compounds and determining crystallographic orientations of microstructural features as small as ~1 μm (recently developed capability--not currently widely used, but likely to become so)

Typical Uses

- Characterizing fracture surface micro-appearance and determining the nature of the fracture process (dimple rupture, cleavage, fatigue, intergranular environmentally enhanced fracture, etc.)
- Quality assurance examination of microelectronic devices, interconnections, bonds, etc.
- Detecting the onset of corrosion in small components and characterizing corrosion products
- Resolving fine microstructural features on polished and etched metallographic samples
- Performing qualitative and semi-quantitative elemental analyses on microstructural features, contaminant particles, etc.
- Identifying microstructural phases and compounds by their crystal structures

- Characterizing preferred crystallographic orientations by analysis of orientations of individual grains

Spatial Resolution

- Secondary electron imaging of surface topography: $\sim$10 nm
- Backscattered electron imaging of atomic number contrast: $\sim$1 μm
- X-ray characterization of elemental chemistry: $\sim$2 μm using typical beam voltages of $\sim$20 kV (much better resolution, $\sim$100 nm, can be obtained using low voltage beams)
- Electron diffraction characterization of crystal structure and orientation: $\sim$1 μm

Elemental Analysis Detection Threshold and Precision

- Threshold sensitivity for elemental analysis using EDS detector: $\sim$1%
- Precision of quantitative elemental analysis using EDS detector: $\sim$10% relative or 2% absolute, whichever is greater

Limitations

- Energy dispersive detectors used for chemical analysis have difficulty detecting and analyzing elements with atomic numbers less than $\sim$7 (nitrogen); older instruments with beryllium window detector cannot detect elements with atomic numbers lower than $\sim$11 (sodium).

Sample Requirements

- Sample size up to $\sim$5 cm can be accommodated by most SEMs, and SEMs equipped with large sample chambers can readily accommodate considerably larger samples, such as 15 and 20 cm silicon wafers from microelectronics production lines.
- No preparation is typically required for clean metal samples.
- Nonconductive samples or samples with marginally conductive surface regions must be coated with a thin layer of conductive material. A thin gold-palladium layer is typically sputtered onto samples intended for imaging only, whereas a thin carbon layer is typically vacuum evaporated onto samples where x-ray microanalysis will be performed.

Operating Principles

Instrumentation. A simplified schematic of an SEM is shown in Fig. 1. Electrons are produced by one of several types of sources at the top microscope column. These electrons are accelerated down the column by a voltage differential in the electron gun (typically in the range of 1,000 to 50,000 V). The column must be kept under vacuum while the microscope is operating. As the beam passes down the microscope column, it is focused by variable strength electromagnetic lenses to a fine spot (in some cases as small as $\sim$1 nm) on the surface of the sample using the *x*-axis and *y*-axis electromagnetic beam scanning coils. The raster rate can be varied by the operator--one complete pass over the area of interest can take as little as $\frac{1}{60}$ s (typically used for lower resolution screening of various areas on the surface), or as long as 20 s (typically used for higher resolution photographing of an area of interest). Several types of detectors are used to monitor the various signals emitted from each spot on the sample as the beam impinges on it. The outputs of these detectors are electronically processed and used to modulate the intensity of the spots on a cathode ray tube (CRT) whose scan is synchronized with that of the electron beam's raster on the sample surface. The result is a television-type image of the portion of the sample surface being scanned by the beam. Portions of the surface that produce strong response signals appear bright on the CRT, while portions that produce weak response signals appear dark.

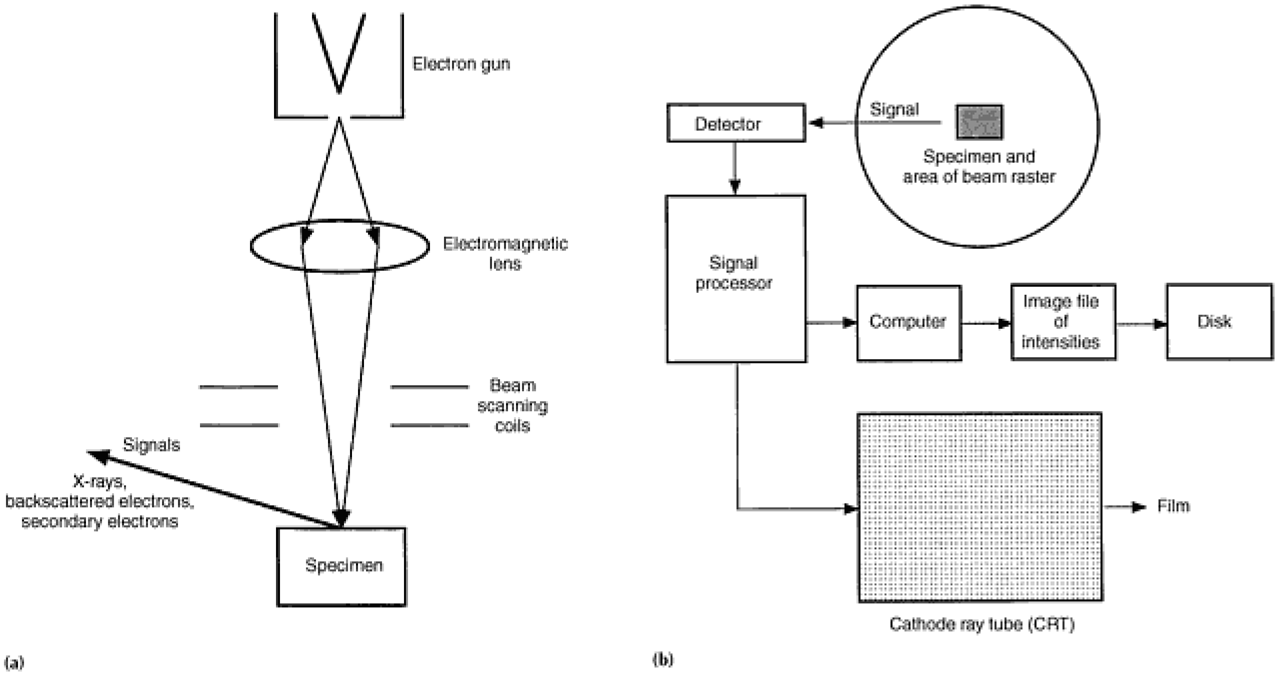

Fig. 1 Schematic of a scanning electron microscope. (a) Electron beam produced and focused to a fine spot on sample surface. Scanning coils enable the position of the beam to be rastered across a selected portion of the sample surface. Signals produced by the sample at the point where the beam impinges include secondary electrons, backscattered electrons, and characteristic x-rays. (b) Detected signals are collected, amplified, and used to modulate the intensity of a cathode ray tube, whose raster is synchronized with that of the beam.

The images viewed on the CRT have historically been recorded photographically, but in recent years are increasingly being recorded electronically. Such electronic recording facilitates electronic image enhancement, quantification of the sizes and shapes of features appearing on the images, electronic transmission of images to other locations, and electronic incorporation of images into reports.

As can be seen from the above description, the SEM really is not a microscope in the classical sense--it has no lenses that magnify the image. The sole purpose of the magnetic lenses is to focus the beam to a very small spot on the sample surface. The magnification of the image is defined by area on the sample surface over which the electron beam is rastered and the size of the CRT screen on which the image is displayed. Magnification is increased simply by decreasing the area over which the beam is rastered, or decreased by increasing the area over which the beam is rastered.

Several types of signals can typically be detected and used to generate images on the CRT. The images corresponding to these different signals reveal different types of information. The three primary types of signals and images, secondary electrons, backscattered electrons, and x-rays, are described in the following paragraphs.

Beam-Sample Interactions. When the incident electron beam impinges on the surface, it penetrates a short distance into the sample, interacting with the atoms in the sample as it penetrates. Typical penetration distances range from one to several micrometers depending on the atomic numbers of the elements in the sample (greater penetration depths for low atomic number elements, lesser depths for high atomic number elements) and the incident beam accelerating voltage (greater penetration for higher accelerating voltages). The beam spreads out as it penetrates, typically resulting in a pear-shaped interaction volume (Fig. 2).

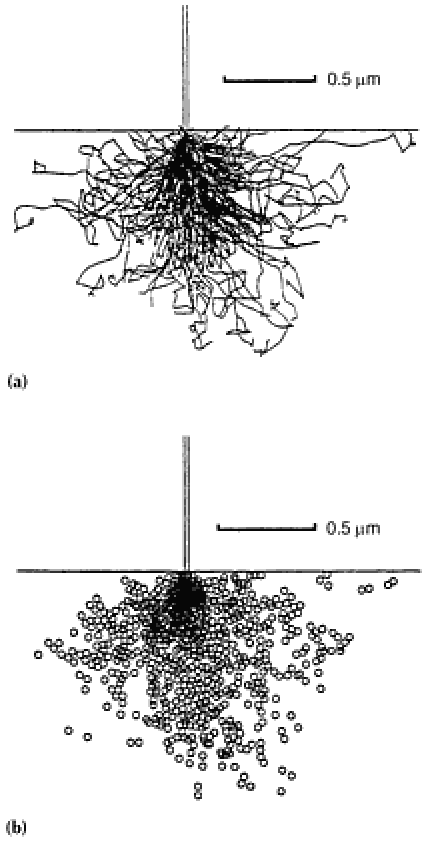

Fig. 2 Monte Carlo simulations of the interaction volume of a 20 keV primary electron beam in an iron sample. (a) Electron trajectories. (b) Sites of K-shell ionizations and production of characteristic x-rays. Source: Ref 1

Two important types of interactions occur between the incident electrons and the sample's atoms, resulting in the three primary signals (Fig. 3). Some of the incident electrons interact with the electrons associated with the atoms of the sample, "knocking them out" of the conduction band and other orbitals, and generating secondary electrons. The atoms from which electrons have been removed are now in "excited states" and "relax" as electrons from higher energy levels fill the vacated sites. Each of these relaxation events is accompanied by the release of energy equal to the difference in energies between the two atomic energy levels involved. Transitions involving inner shell electrons often result in the generation of energy levels involved. Transitions involving inner shell electrons often result in the generation of x-ray photons. This is identical to the atomic process described in the section on x-ray fluorescence spectroscopy in the article "Bulk Elemental Analysis." As in x-ray fluorescence spectroscopy, the energies of these x-rays can be compared to the known characteristic energies of each element, enabling the atoms in the sample to be chemically identified, as illustrated in Fig. 3 of that same article. Each incident electron typically interacts with tens to hundreds of atoms before its energy is eventually expended. Each time an incident electron interacts with an atom in this way, its path is deflected somewhat. This accounts for the spreading of the beam as it enters the sample and the pear-shaped interaction volume, as illustrated in Fig. 2 of the article "Bulk Elemental Analysis." Other incident electrons interact with the much heavier nuclei of the atoms in the sample. These electrons typically "bounce back," as would a ping pong ball striking a bowling ball. For obvious reasons, these are termed backscattered electrons.

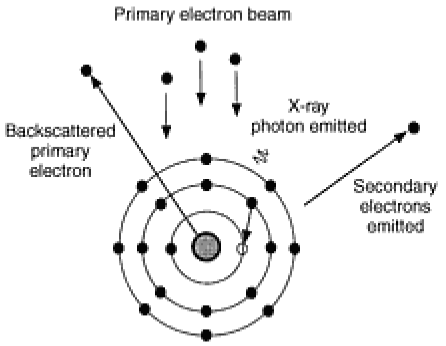

Fig. 3 Interaction of the primary electron beam with atoms in the sample resulting in backscattered primary electrons, secondary electrons, and characteristic x-rays

Secondary Electron Imaging of Surface Topography. Secondary electron images provide information on the topography of the same--a "picture" of the portion of the sample surface over which the beam is being rastered. The secondary electrons generated in the sample have relatively low energies, on the order of a few electron volts (eV). As a result, only the secondary electrons produced close to the sample surface (within ∼10 nm) are able to escape from the sample. Secondary electrons produced deeper in the interaction volume interact with other atoms, dissipate their energies, and are absorbed before reaching the surface (Fig. 4). The secondary electrons emitted from the sample are attracted to the secondary electron detector by a positive bias of several hundred volts. Because the secondary electrons have kinetic energies of only a few electron volts, their paths are easily influenced by this bias, and a high percentage of them enter the detector and are counted.

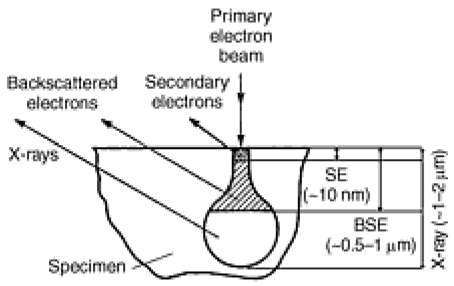

Fig. 4 Regions in the interaction volume from which various signals escape. SE, secondary electrons; BSE backscattered electrons

The number of secondary electrons exiting the sample is controlled mostly by the local geometry of the surface at the point where in incident beam impinges on it. As can be seen in Fig. 5, when the beam impinges on a rough sample at the top of a sharp peak, a great deal of the interaction volume is within ∼10 nm of a free surface, hence a very large number of secondary electrons exit the sample and are collected by the detector. The resulting intense signal results in a bright spot on the CRT. Conversely, when the incident beam impinges at the bottom of a deep valley, very little of the interaction volume is within ∼10 nm of a free surface, hence a very few secondary electrons exit the sample, resulting in a dark spot on the CRT. For inclined surfaces, the number of escaping secondary electrons increases with increasing angle of inclination (Fig. 5).

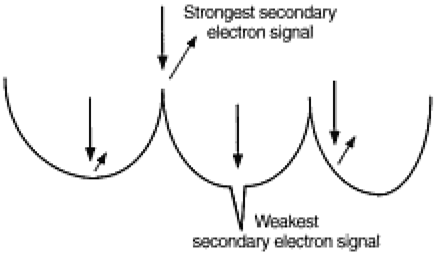
Strongest secondary electron signal
Weakest secondary electron signal

Fig. 5 Effect of local surface geometry on secondary electron signal strength. Cross section of rough surface illustrating that strongest secondary electron signals originate from tops of sharp peaks, strength of secondary electron signal decreases with increasing angle between the primary beam and the sample surface, and weakest secondary electron signals originate from deep holes.

The net result is that, in secondary electron images, sharp peaks appear brightest, highly inclined edges appear somewhat less bright, portions of the surface perpendicular to the beam appear darker, and the bottoms of deep recesses appear darkest. This is very similar to the pattern of contrast that results when inclined visible light impinges on a macroscopically rough surface. Our brains are accustomed to "processing" images with this type of contrast, and correctly interpret secondary electron images as topography or pictures of the sample's surface.

These principles of secondary electron contrast are apparent in the SEM photograph or a dimpled fracture surface, shown in Fig. 6. The surface consists of cup-shaped dimples, each corresponding to a microscopic failure event, and sharp ridges where adjacent failure events joined. The secondary electron image reveals the ridges as bright, the inclined dimple walls as less bright, and the perpendicular dimple bottoms are darker.

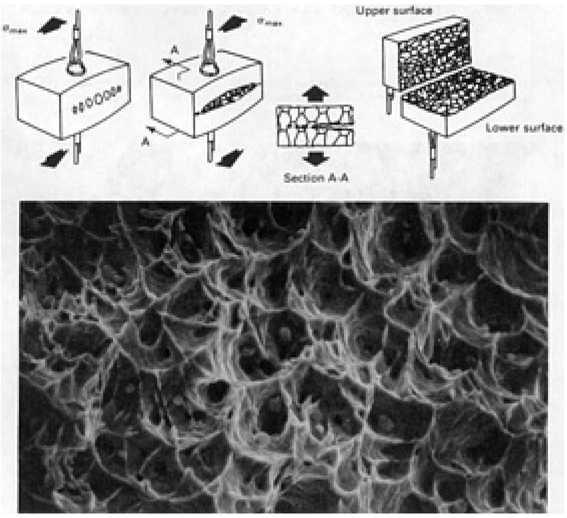

Fig. 6 Secondary electron image of dimples on ductile fracture surface. Source: Ref 2

Because secondary electrons are collected from only the top ~10 nm of the sample where very little beam spreading has occurred, each digital examination point on the sample surface can be quite small and still be distinct from neighboring examination points. As a result, it is possible to resolve adjacent surface features with dimensions of ~10 nm by secondary electron imaging or less under special conditions. State of the art instruments with field emission electron guns have ~1 nm secondary electron imaging resolution. Furthermore, the primary requirement for a sharp image is that the incident beam be focused to sharp spot on each digital examination point at which it impinges on the surface. Because the cone angle of the focused beam can be made quite small, it is possible to satisfy this requirement simultaneously for both peaks and valleys on relatively rough surfaces. This provides outstanding depth of field, which is the ability to focus simultaneously on both the highs and lows of rough surfaces.

In addition to imaging naturally rough surfaces, such as metal fractures, secondary electron imaging can also be used to examine the surfaces of polished and etched metallographic samples. The fact that secondary electron imaging can resolve features ~100 times smaller than can be resolved by light microscopy enables SEMs to use higher magnifications to characterize fine microstructural features that cannot be resolved by light microscopy (Fig. 7).

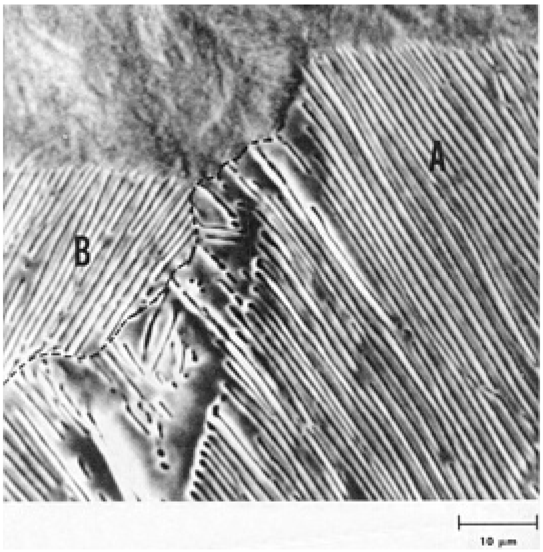

Fig. 7 Secondary electron image of polished and etched sample of Fe-0.8%C showing details of pearlite (A and B) growing into austenite (transformation interrupted by quenching). Source: Ref 3

Backscattered Electron Imaging and Atomic Number Contrast. Backscattered electron images, on the other hand, provide contrast based on differences in average atomic number of different portions of the sample. Because backscattered electrons result from direct collision of light incident electrons with the heavy nuclei of atoms in the sample, it is not surprising that the strength of the backscattered electron signal increases with increasing nuclear mass, that is, with increasing atomic number. Backscattered electrons exit the sample with kinetic energies similar to those for the incident electrons (thousands of electron volts), so their paths are essentially unaffected by the few hundred volt bias of the secondary electron detector. Backscattered electrons are typically collected by solid state annular detectors placed above the sample to maximize the number of electrons that can be collected in a line-of-sight fashion. Backscattered electron images display portions of the sample surface with relatively high average atomic number as bright; portions of the sample surface with lower average atomic number appear darker (Fig. 8).

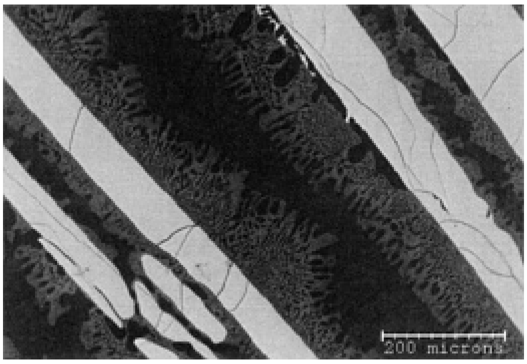

Fig. 8 Backscattered electron image showing atomic number contrast in as-cast Cu-Al-Mg alloy. Brightest areas represent phases containing the greatest concentration of high atomic number copper. Darker areas represent phases of progressively lower average atomic number. Courtesy of Joe Michael, Sandia National Laboratories

Because backscattered electrons have higher kinetic energies than secondary electrons, they can escape from far deeper in the interaction volume. Because the beam diverges as it penetrates in the sample, backscattered electron image spatial resolution is not as good as that of secondary electron images. Backscattered electron resolution is typically ~1 μm, similar to that of light microscopy. This resolution can be improved to ~100 nm by using low voltage beams. Excellent depth of field is retained with backscattered electron imaging, for the same reason discussed for secondary electron imaging.

X-Ray Detection and Elemental Microanalysis. X-rays provide information on which elements are present in small portions of the sample. The atomic principles by which the characteristic x-rays are generated are identical to those discussed in the section on x-ray fluorescence spectroscopy in the article "Bulk Elemental Analysis," except that excitation is provided by the incident electron beam, rather than an incident x-ray beam. In effect, then, the scanning electron microscope provides a mini-x-ray spectrometer with a very fine incident beam that can be used to probe the chemistries of very small operator-selected portions of the sample.

Many scanning electron microscopes are equipped with an energy dispersive x-ray detector. The operation and characteristics of EDS detectors are described in the section on x-ray fluorescence spectroscopy in the article "Bulk Elemental Analysis." This detector and the associated electronics provide a histogram of the x-ray energies emitted from the sample. As with bulk x-ray spectroscopy, the characteristic x-ray energies observed tell which elements are present, and the relative intensities of the various characteristic x-ray peaks provide information on the relative concentrations of the elements present, as illustrated in Fig. 3 of that same article.

X-ray spectra can be collected either from an area on the surface defined by the beam's *x-y* raster, or from an individual point by stopping the raster and adjusting the scan coils to move the beam to the desired location on the sample surface. In either case, x-rays are typically collected for tens to hundreds of seconds, and the x-ray histogram displayed on a second CRT, rather than the CRT used for imaging. The results of most analyses are displayed as secondary electron images with x-ray spectra corresponding to particular features of interest (Fig. 9).

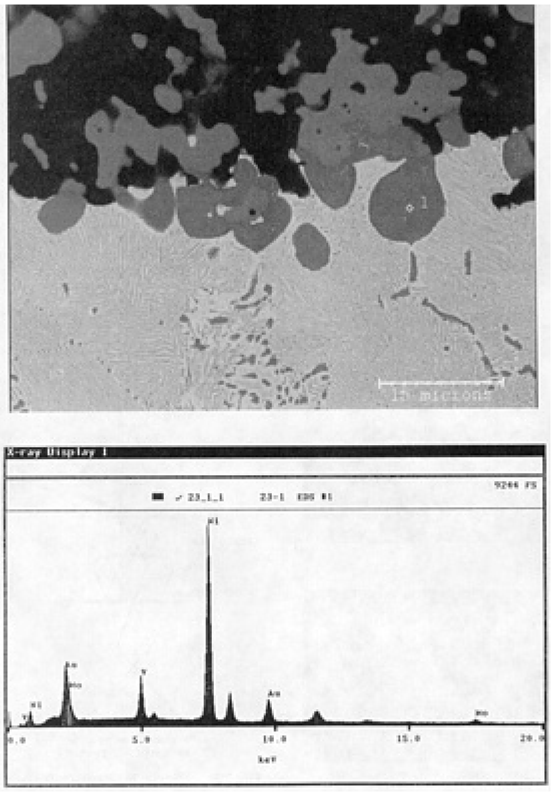

Fig. 9 Backscattered electron image of 82%Au-15.5%Ni-1.75%V-0.75%Mo active braze alloy joined to Mo-Al_2O_3 cermet. Accompanying x-ray spectrum obtained from area 1 shows the phase forming at the interface to be rich in nickel and vanadium. Courtesy of Bonnie McKenzie, Sandia National Laboratories

If desired, a single x-ray energy can be selected corresponding to an element of interest, the instrument returned to the scanning mode, and an image generated in which the brightness is modulated by the concentration of this element at each point on the raster. The resulting x-ray maps can provide exceptionally useful information on how various elements are distributed in the sample, particularly when taken in conjunction with secondary electron or backscattered electron images. However, because energy dispersive x-ray detectors are characterized by a moderate level of background noise, the x-ray maps they generate are not as high in quality as ones generated when the x-rays are analyzed using wavelength dispersive crystal spectrometers. (See Fig. 4-6 in the section "X-Ray Fluorescence Spectroscopy" of the article "Bulk Elemental Analysis" for discussion of the strengths and weaknesses of these different types of x-ray detectors.) Scanning electron microscopes are occasionally equipped with a wavelength dispersive detector to facilitate x-ray mapping, but more often such mapping is done using an electron probe microanalyzer, as will be described in the next section.

Characteristic x-ray escape the sample from the entire interaction volume (Fig. 4). As a result, the spatial resolution for x-ray microanalysis is on the order of several micrometers. It is a common misconception that SEMs can perform chemical analyses with the same resolution as secondary electron imaging. While surface features as small as ~10 nm can be "seen" by secondary electron imaging, chemical analyses of such features really provide elemental information on not only the feature itself, but the entire several micrometer volume surrounding it.

As with bulk x-ray fluorescence spectroscopy, only elements with atomic numbers of ~7 or greater can be readily detected and analyzed. Elements with lower atomic numbers produce very few x-rays, and the x-rays produced have very low energies and are easily absorbed. Older instruments equipped with beryllium window detectors are limited to elements with atomic numbers of 11 or higher because the low energy x-rays produced by lower atomic number elements are mostly absorbed in the detector window. More modern ultrathin window detectors enable detection of elements down to atomic number ~5. Lower atomic number elements must be detected by other means, as will be described in the section on Auger electron microscopy.

Diffracted Beams and Crystallographic Microanalysis. Recent developments have also made it possible to collect and analyze crystallographic information from features observed in the SEM. The divergent beam of characteristic x-rays generated as the incident electron beam penetrates the sample can also be diffracted from the portion of the sample in the immediate vicinity of the beam interaction zone. The resulting diffraction pattern, termed a Kossel pattern, is particularly useful for measuring interplanar spacings with high precision. The precise interplanar spacing information can, in turn, be used to measure residual stresses in individual grains. The divergent beam of backscattered electrons also has a wave character and can similarly diffract from the planes in the surrounding grain. The resulting electron diffraction pattern, termed a Kikuchi pattern, is analogous to the x-ray Kossel pattern, but is made up of straight lines that are easier to index. These Kikuchi patterns can be used to identify crystalline phases (similar to x-ray powder diffraction but based on a different diffraction geometry), as well as to determine orientation distribution functions in a grain-by-grain fashion. These Kossel and Kikuchi patterns can be readily solved and interpreted by computer methods. An example of a Kikuchi pattern and its computer assisted solution are shown in Figure 10. Most SEMs are not yet equipped to perform these types of crystallographic analyses, but it is likely that these powerful capabilities will become more commonly available.

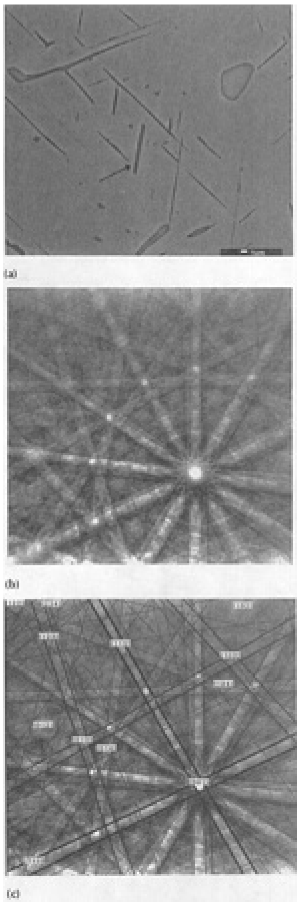

Fig. 10 Kikuchi pattern identification of sigma phase in stainless steel following exposure to elevated temperature. (a) Backscattered electron image. Arrow indicates the dark sigma phase identified by the Kikuchi patterns. (b) Backscattered electron Kikuchi pattern. (c) Computer solution of Kikuchi pattern. Courtesy of Joe Michael, Sandia National Laboratories

Voltage Contrast and Analysis of Microelectronic Devices. Additional types of specialized imaging can also be done with scanning electron microscopes. Several types are particularly useful in examining and analyzing active microelectronic devices. For example, because secondary electrons escape from the sample with kinetic energies of only a few electron volts, the strength of the secondary electron signal will vary substantially with the voltages presenting various parts of an operating electrical device. For the simplest case of a DC device in which potential differences of a few volts exist, more secondary electrons will be emitted from negatively biased portions, and fewer from positively biased portions. In the secondary electron image, then, the negatively biased portions will appear bright and the positively biased portions will appear dark. In the more complex case of microelectronic circuit operating at high frequency, strobe-like "pictures" of the circuit's operation can be obtained by rapid "blanking" of the incident beam synchronously with the device, such that each "picture point" on the secondary electron image corresponds to the same "phase" in the circuit's operation. A series of such "strobe images" can be taken corresponding to successive phases in the circuit's operation, showing the potentials of different conduction lines and circuit elements at each phase, which provides a powerful tool for troubleshooting microelectronic circuits.

Capabilities of Related Techniques:

Electron probe microanalysis is very similar to SEM, but usually equipped with several crystal spectrometers for wavelength dispersive x-ray analysis. This provides greatly improved capabilities for quantitative microanalysis, x-ray mapping, and characterizing elemental profiles in the vicinities of interfaces. Flat polished samples are required in order to take full advantage of quantification capabilities.

Transmission electron microscopy provides markedly better spatial resolution for imaging and x-ray microanalysis, and provides for crystallographic analysis by electron diffraction. Crystallographic analysis methods are more highly developed than those for SEM. Sample preparation is tedious, and only very small portions of the sample can be viewed.

Scanning Auger Microscopy can perform microanalyses on low atomic number elements down to lithium (atomic number 3). Analyses originate from very near surface region (first few atomic layers), so sample surfaces must be atomically clean or results will be representative of surface contaminants rather than the underlying sample.

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1. J. Goldstein et al., *Scanning Electron Microscopy and Microanalysis,* 2nd ed., Plenum, 1992, p 85
2. B. Gabriel, *SEM: A User's Manual for Materials Science,* American Society for Metals, 1985, p 110
3. *Materials Characterization,* Vol 10, *ASM Handbook,* ASM International, 1986

Electron Probe Microanalysis (EPMA)

Capabilities and Typical Uses

The electron probe microanalyzer (frequently termed the electron microprobe) is essentially a scanning electron microscope that has been optimized to perform high quality elemental microanalyses. Historically, the two instruments were developed separately and for different purposes, but as they evolved they became increasingly similar. While most SEMs are primarily imaging instruments to which rapid elemental microanalysis capabilities have been added, electron microprobes are primarily quantitative microanalyzers that are capable of imaging the areas being analyzed. Electron microprobes are used primarily for the following:

- Quantitative microanalyses of microstructural features
- Quantitative elemental profiling of compositional gradients (similar to Fig. 22b, but with $\sim$1 μm spatial resolution)
- X-ray mapping to show how elements of interest are concentrated or depleted in different micro-areas or microstructural features (Fig. 11)

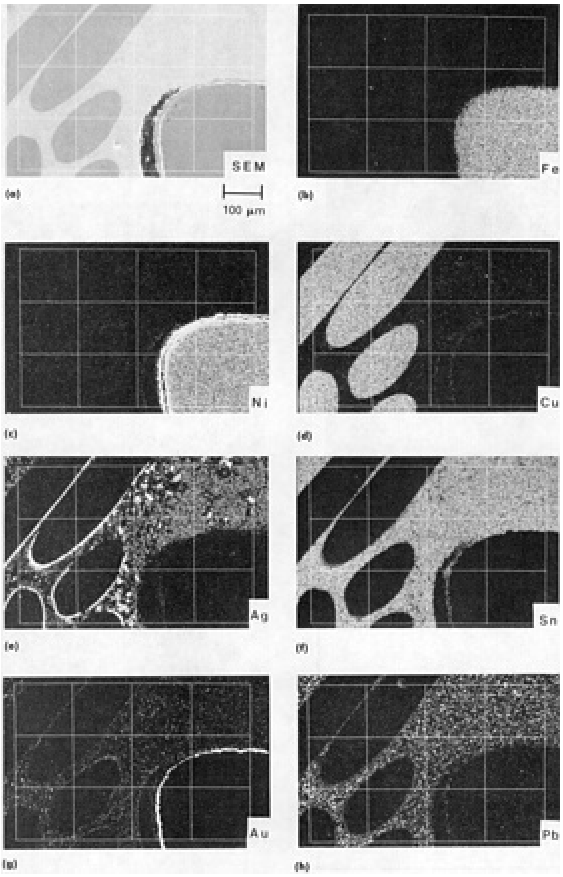

Fig. 11 Electron microprobe elemental map showing distributions of elements in stranded wire soldered to a terminal pin. (a) Backscattered electron image. (b-h) Elemental maps showing locations and concentrations of iron, nickel, copper, silver, tin, gold, and lead, respectively. Source: Ref 3

Operating Principles and Instrumentation

The electron microprobe and scanning electron microscope operate on identical principles. The key differences are that electron microprobes are typically equipped with several crystal spectrometers to facilitate wavelength dispersive x-ray analysis. Qualitative analysis is typically performed using an energy dispersive x-ray analysis. Qualitative analysis is typically performed using an energy dispersive x-ray detector, but subsequent quantitative analyses are done using the wavelength dispersive crystal spectrometers (WDS). As described in the section on x-ray fluorescence spectroscopy in the article "Bulk Elemental Analysis" and illustrated in Fig. 4-6, wavelength dispersive x-ray analysis has several advantages over energy dispersive analysis:

- Much better signal-to-noise ratio, which facilitates qualitative analysis and the generation of much higher quality x-ray maps
- Better separation of x-rays with similar energies (or wavelengths), which enables elements that are difficult to distinguish with EDS detectors, such as molybdenum and sulfur, to be unequivocally identified and quantified
- Better detection of low atomic number elements that produce small numbers of low energy x-rays. Electron microprobes can identify and semi-quantify elements with atomic numbers in the 4 to 7 range, which are more difficult to detect and analyze with EDS systems.

Other key factors to be considered include:

- Electron microprobes have high and very stable beam currents to maximize x-ray counting statistics and minimize variations in x-ray generation rate associated with instrumental fluctuations.

- Electron microprobes have precisely controlled automated specimen stages to facilitate large numbers of composition measurements to be made in an automated computer controlled fashion.
- Electron microprobes are equipped with sophisticated computer hardware and software to facilitate data reduction and quantitative plotting and mapping of results.

Spatial Resolution

- Backscattered electron imaging of atomic number contrast: ~1 μm
- X-ray characterization of elemental chemistry: ~2 μm, sampling depth ~2 μm

Elemental Analysis Detection Threshold and Precision

- Threshold sensitivity for elemental analysis using WDS detector: ~0.01%
- Precision of quantitative elemental analysis using WDS detector: ~0.5% relative or 0.02% absolute, whichever is greater

Limitations

- Precise quantitative chemical analysis is difficult for atomic numbers less than ~8 (oxygen), and must frequently be inferred from analytical totals less than 100%.
- Elements with atomic number less than ~4 (beryllium) cannot be detected.

Sample Requirements

- The best quantitative analyses are obtained on polished and unetched metallographic samples. Samples with rough, scratched, or etched surfaces violate some of the assumptions inherent in the data reduction software, thus degrading the precision of the quantitative analytical results.
- Nonconductive samples or samples with marginally conductive surface regions must be coated with a thin layer of conductive material, typically carbon.

Capabilities of Related Techniques

X-Ray fluorescence spectroscopy (XRF) provides bulk elemental analysis. X-ray fluorescence spectroscopy instruments equipped with fine beam and x-y scanning capabilities provide elemental mapping on much larger samples but with much poorer spatial resolution.

Transmission electron microscopy (TEM) provides markedly better spatial resolution for x-ray microanalysis but at the expense of poorer counting statistics uncertainty. TEM sample preparation is tedious, and only very small portions of the sample can be viewed.

Scanning Auger microscopy (SAM) can perform microanalyses on low atomic number elements down to lithium (atomic number 3), but analyses are less quantitative. Analyses originate from very near surface region (first few atomic layers), so sample surfaces must be atomically clean or results will be representative of surface contaminants rather than the underlying sample.

Reference cited in this section

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Transmission Electron Microscopy (TEM)

Terminology

Transmission electron microcopy (TEM) has been used since the 1950s to obtain very high resolution images of microstructures. As TEMs were enhanced to include features such as digitally scanned point beams and energy dispersive x-ray detectors for chemical microanalysis, alternative names, such as scanning transmission electron microscopy (STEM) and analytical electron microscopy (AEM), were coined and became commonly used. This section incorporates all of these under the general title transmission electron microscopy.

Capabilities

The transmission electron microscopy provides the highest resolution imaging, elemental analysis, and crystallographic analysis of all the techniques described in this article. It is capable of:

- Imaging of features as small as several tenths of nanometers, down to the scale of individual crystallographic planes and atoms
- Qualitative and semi-qualitative elemental analyses with spatial resolution approaching 10 nm, roughly 100 times better than SEMs or electron microprobes
- Identifying crystalline compounds and determining crystallographic orientations of microstructural features as small as 30 nm

Typical Uses

The combination of capabilities described above make the TEM a very powerful tool for high resolution microstructural characterization. Typical uses include:

- Characterizing dislocation arrangements resulting from deformation and annealing
- Identifying and characterizing the morphologies, elemental compositions, and crystallographic aspects of very fine microstructural features, e.g., strengthening precipitates produced during age hardening
- Determining orientation relationships between parent and product phases, matrix and twins, etc.
- Characterizing compositional gradients over very short distances, e.g., diffusion profiles associated with phase transformations
- Determining phase diagrams by characterization of microstructural phase equilibria

Spatial resolution

- Imaging: ~0.2 nm
- X-ray characterization of elemental chemistry: ~10 nm
- Electron diffraction characterization of crystal structure and orientation: ~30 nm

Elemental Analysis Detection Threshold and Precision

- Threshold sensitivity: ~1%
- Precision of quantitative elemental analyses: ~10% relative or 2% absolute, whichever is greater

Limitations

- Sample preparation is tedious, and only small portions of the sample can be analyzed.
- Elemental chemical analysis cannot be readily done for elements with atomic numbers less than ~7, and counting statistics are not as good as with EPMA.

Sampling Requirements

- Small samples must be carefully prepared specifically for TEM, as described below. Sample preparation is tedious.
- Care must be taken to ensure that samples are free from preparation artifacts.

- Only very small portions of the sample can be analyzed, so it is crucial to ensure that the microstructure characterized is representative of the bulk material.

Operating Principles

Instrumentation. A simplified schematic of a TEM is shown in Fig. 12. The top portion of the column is similar to that of an SEM. Electrons are produced and are accelerated down the column by a voltage differential in the electron gun typically in the range of 100,000 to 400,000 V). The column must be kept under vacuum while the microscope is operating. As the beam passes down the microscope column, it is focused by variable strength electromagnetic condenser lenses. These condenser lenses can either focus the beam to a fine spot on the sample or flood a much larger portion of the sample with a parallel beam of electrons.

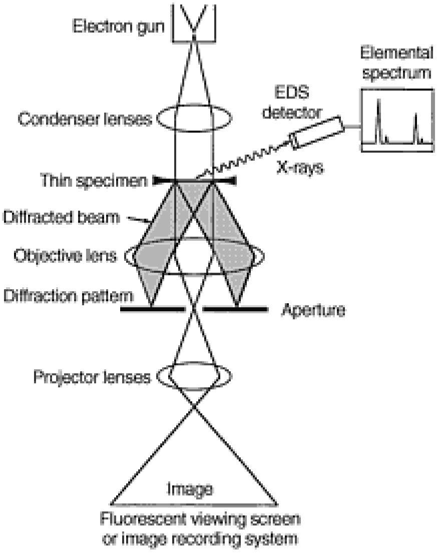

Fig. 12 Schematic of transmission electron microscope, shown operating in the conventional parallel beam mode. The beam can also be focused to a small spot and rastered over the sample. Courtesy of Tom Headley, Sandia National Laboratories

Sample Preparation. The sample typically consists of a 3 mm diameter disk of material that has been specially prepared so that a portion of it is thin enough to permit the electron beam to penetrate completely through it. The maximum permissible thickness varies with the elements making up the sample (high atomic number elements are less transmissive) and the beam accelerating voltage (higher accelerating voltages enhance beam penetration), but it is typically in the range of one hundred to several hundred nanometers. Samples are thinned by a variety of methods including mechanical cutting and grinding (used in the preliminary steps of sample preparation), electrolytic polishing (commonly used for final thinning of metals), and ion milling (used with both metals and insulating materials). It is crucial that any damaged layer introduced during preliminary mechanical preparation be fully removed during subsequent electropolishing or ion milling. Typically these preparation steps are done in a way that produces an hourglass cross section in the disk, as shown in Figure 13. Final thinning is continued until a hole first forms near center of the disk, then the electropolishing or ion milling processes are immediately halted. The thin tapered portions of material adjacent to the hole are frequently thin enough to be electron transparent. If electropolishing or ion milling are continued too long, the thin electron transparent sections adjacent to the hole will be removed and the remaining material will likely be too thick to be penetrated by the electron beam.

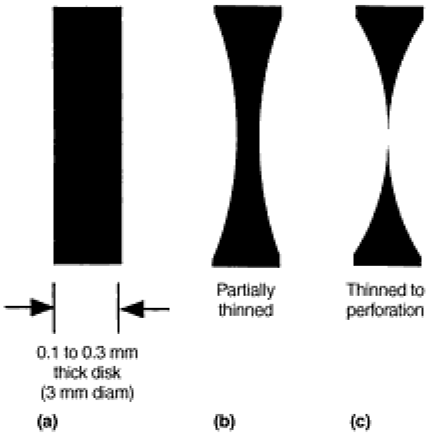

Fig. 13 Steps in TEM specimen preparations. (a) A disk with an ~3 mm diameter and 0.1 to 0.3 mm thick is cut from the bulk sample. (b) The disc is thinned preferentially at its center (typically by fine mechanical grinding, chemical, or electrochemical methods), producing an hourglass profile. (c) Final thinning (typically by electrochemical or ion beam methods) is continued until a hole forms. The very thin material around the hole is usually thin enough to be penetrated by the TEM electron beam.

As the preceding description implies, TEM sample preparation is a tedious and time consuming process. Even when the sample preparation process is successful, only a very small portion of the sample is electron transparent and amenable to characterization. Because the results of TEM analyses represent information obtained from very small amounts of material, it is exceedingly important to ensure that the material being characterized is representative of the bulk material. Hence, TEM should usually be done in conjunction with other types of analysis, such as metallography, x-ray diffraction, and scanning electron microscopy, which readily characterize much larger amounts of material, albeit with lower resolution. Transmission electron microscopy is an exceptionally powerful method for characterizing microstructural details, but it is important to balance this detailed look at the "leaves" with a good overview of the "forest."

Beam-Sample Interactions. Once a sample with adequate electron transparency has been inserted into the microscope, a wealth of crystallographic, morphological, and chemical information can be obtained from it. As the incident electron beam penetrates a crystalline sample a variety of diffraction and excitation events occur. These provide:

- Identification of phases and compounds based on interplanar spacing fingerprints obtained from electron diffraction patterns (equivalent to x-ray powder diffraction, but on very small preselected microstructural features)
- Determination of crystallographic orientations from single-crystal electron diffraction patterns (equivalent to x-ray Laue orientation determination, but on very small grains, precipitates, or other microstructural features)
- Imaging of microstructural features (similar to metallography, but with ~1000 times better resolution, and based on a diffraction contrast, rather than reflected light contrast)
- Elemental analysis (qualitative and quantitative) based on characteristic x-ray emission (equivalent to elemental analysis in the SEM or EPMA, but with 10 to 100 times better spatial resolution)

Electron Diffraction. Because the electron beam has a wave character, it can be diffracted by the planes in the crystal in cases where Bragg's law is satisfied, essentially as was described in the previous article on "X-Ray Diffraction for Bulk Structural Analysis" and illustrated in Fig. 2 in that article. If such diffraction occurs from a large number of fine randomly oriented crystals in the sample, this results in a series of axisymmetric cones, each cone corresponding to a specific interplanar spacing and the associated diffraction angle that satisfies Bragg's law. These cones intersect the viewing screen as circular rings, and can be recorded either on the underlying film or CCD detector as rings. The radius of each ring can be measured and used to calculate the diffraction angle and corresponding interplanar spacing. The set of interplanar spacings can then be used to identify the crystalline phases or compound(s) making up the sample, exactly as was described in the article "X-Ray Diffraction for Bulk Structural Analysis." An example of this is shown in Figure 14.

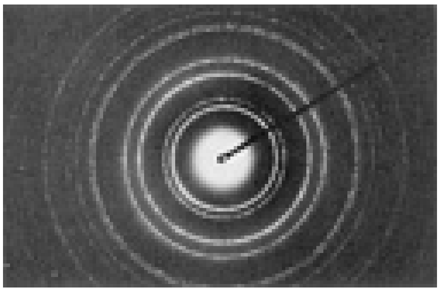

Fig. 14 Electron diffraction ring pattern obtained from numerous grains in a polycrystalline aluminum sample. Starting with the innermost ring, the rings correspond to {111}, {200}, {220}, {311}, and {222} planes. Source: Ref 3

Alternatively, if the electron beam impinges on a single grain or crystal, an electron diffraction pattern consisting of a series of spots is obtained. This pattern is similar to a single crystal x-ray Laue pattern. The symmetry and angular relationships between the spots enable the crystallographic orientation of the grain to be determined. Figure 15 shows an example of orientation determination from a single crystal electron diffraction pattern. In cases of related orientations, such as epitaxial nucleation of one phase on another, or the formation of oriented precipitates with a parent phase, the orientation relationships between the phases can be determined from these electron diffraction patterns.

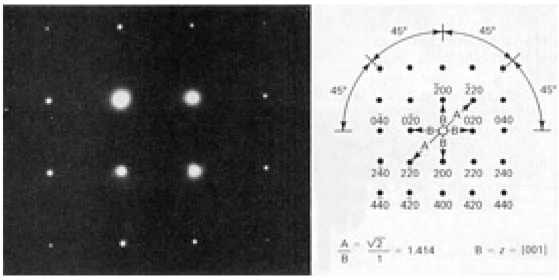

Fig. 15 Electron diffraction spot pattern from a single grain in a polycrystalline aluminum sample. The spots are indexed in the accompanying computer-generated drawing. Source: Ref 3

Imaging of Microstructural Features. Electron diffraction also provides the primary source of image contrast in metals and other crystalline materials. Consider a relatively broad incident beam that impinges uniformly across several grains in a thin sample (Fig. 16). Electron beams in the range of 100,000 to 400,000 V have much shorter wavelengths than x-rays, which makes typical diffraction angles quite small. As a result, nearly all grains diffract to some extent. Some grains are oriented in ways that particular planes satisfy Bragg's law precisely. These grains diffract strongly. Other grains are oriented in ways that none of their planes satisfy Bragg's law precisely, but some planes are within a small fraction of a degree, hence they diffract to a limited extent.

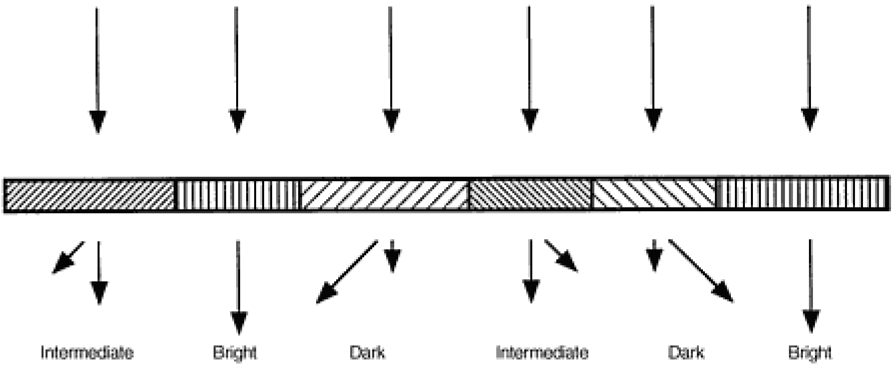

Fig. 16 Development of TEM image contrast due to differential diffraction. Grains that are poorly oriented for diffraction transmit a higher percentage of the beam and appear bright in the image; those ideally oriented for diffraction transmit a lower percentage of the beam and appear dark in the image.

The degree to which diffraction occurs varies the extent to which the incident beam is directly transmitted through the sample from grain to grain. Grains least oriented for diffraction directly transmit much of the incident beam and diffract only a small amount of it. Other grains are ideally oriented for diffraction and directly transmit much less of the incident beam and diffract much of it. The directly transmitted beam, then, it not uniform in intensity across its diameter but carries intensity variations corresponding to the grains through which it passed and their differing level of diffraction. When the directly transmitted beam is imaged, magnified, and projected onto the viewing screen, this provides light and dark contrast in the image. Grains that transmitted a high percentage of the incident beam appear bright, and those that diffracted more of the incident beam appear dark. Figure 17 shows an example of this type of grain contrast.

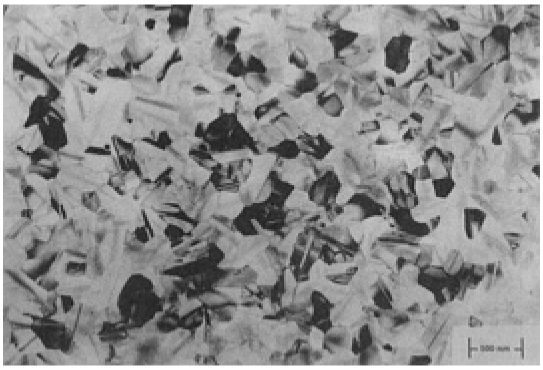

Fig. 17 Transmission electron microscopy grain orientation contrast in a sample of fine-grained polycrystalline silicon. Courtesy of Tom Headley, Sandia National Laboratories

In addition to contrast arising from grain-to-grain orientation differences, any crystalline defects that result in local variations in diffraction also produce light and dark contrast in the image. As a result, defects such as dislocations and stacking faults can be imaged by the TEM. Figure 18 shows an example of dislocations in aluminum imaged by TEM.

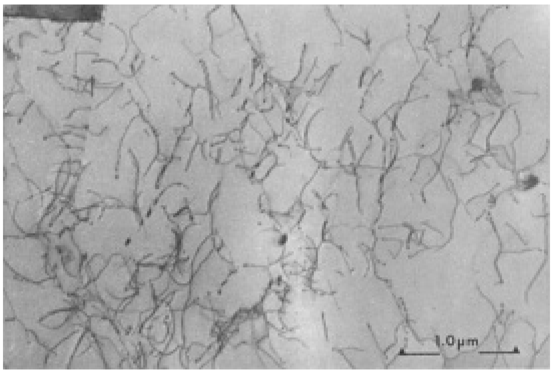

Fig. 18 Transmission electron microscopy imaging of dislocations in aluminum. Source: Ref 3

In addition to the bright field images obtained from the directly transmitted beam, dark field images can also be obtained from any of the diffracted beams. These images are particularly useful in cases where two or more superimposed diffraction patterns are obtained corresponding to adjacent features in the sample. Dark field imaging makes it possible to determine which diffraction spots correspond to each feature, thus facilitating the determination of crystallographic characteristics such as orientation relationships and habit planes. An example of a dark field image obtained from multiple defraction spots is provided in Fig. 19.

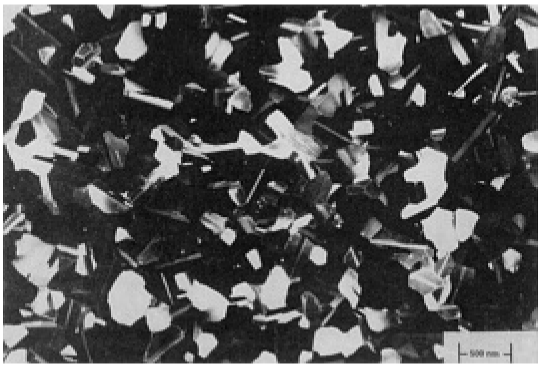

Fig. 19 Transmission electron microscopy dark field image of same area as in Fig. 17. Dark field image was obtained by imaging numerous diffraction spots, so most areas that strongly diffracted and appeared dark in Fig. 17 now appear bright. Areas that diffracted weakly and appeared bright in Fig. 17 now appear dark. Courtesy of Tom Headley, Sandia National Laboratories

Direct imaging of particular crystal planes can be accomplished using a combination of the directly transmitted beam and one or more diffracted beams. This enables high-resolution characterization of individual lattice planes and defects, as illustrated in Fig. 20.

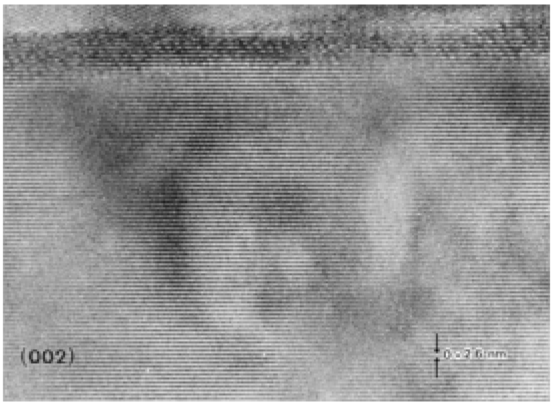

Fig. 20 High-resolution TEM lattice image of zinc oxide formed by combining transmitted and (002) diffracted beams. The interplanar spacing is 0.26 nm. A grain boundary, inclined to the incident beam, is visible in the upper portion of the micrograph. Source: Ref 3

Excitation and characteristic x-ray production also occurs as the incident electron beam interacts with the atoms in the sample. As in the SEM and EPMA, this provides the equivalent of a x-ray fluorescence spectrometer that can probe the chemistries of very small operator-selected portions of the sample. The energies and intensities of these characteristic x-rays are typically detected and analyzed using an EDS system, enabling qualitative identification of the elements present in the sample and quantitative determination of their relative concentrations, respectively. It the TEM, however, the thinness of the sample significantly reduces the size of the interaction volume, as shown in Fig. 21. This occurrence limits the degree to which electron beam spreading occurs in the sample, and provides the ability to perform chemical analyses with significantly better spatial resolution than in the SEM or EPMA. This resolution permits chemical characterization of features as small as 10 nm and determination of chemical gradients over submicrometer distances, as shown in Fig. 22. Because the interaction volume is much smaller than in bulk samples, however, much smaller numbers of x-ray photons are produced. This results in poorer counting statistics, so quantitative analyses obtained by TEM typically have larger degrees of uncertainty than those obtained by EPMA.

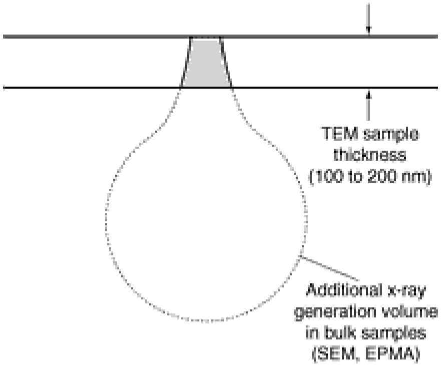
TEM sample thickness (100 to 200 nm)
Additional x-ray generation volume in bulk samples (SEM, EPMA)

Fig. 21 X-ray generation volume in thin TEM samples. Note that the thin sample results in reduced spreading of the incident electron beam, thus reducing the diameter of the x-ray generation region and providing better spatial resolution for elemental microanalysis than is possible with typical thick SEM or EPMA samples.

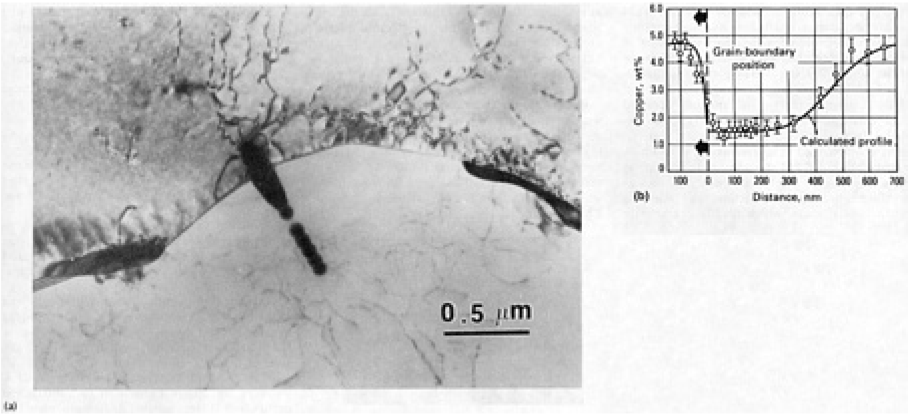
0.5 μm
(a)
(b)
Copper, wt%
Grain-boundary position
Calculated profile
Distance, nm
6.0
5.0
4.0
3.0
2.0
1.0
0
100
0
100
200
300
400
500
600
700

Fig. 22 Copper concentration profile measured by TEM adjacent to the grain boundary in an aged Al-4.7%Cu alloy. (a) Transmission electron microscopy image showing large $CuAl_2$ precipitates along boundary at left and right sides. Dark spots near the center correspond to probe positions during x-ray microanalysis. (b) Composition profile across the grain boundary. Source: Ref 3

The exceptional utility of TEM is based on its ability to obtain imaging, chemistry, and crystallographic information in combination with one another, and with very high spatial resolution (on very small microstructural features). Figure 23 provides a typical example of how these capabilities can be combined to understand microstructural phenomena in great detail. However, these strengths are seriously offset by the difficulty of specimen preparation and the fact that not only very small amounts of material are examined. Scanning electron microscopy and EPMA require much simpler sample preparation and can readily locate and characterize specific areas of interest in larger samples, including failed engineering components. Until recently, SEM and EPMA were capable only of combined imaging and chemical characterization but not crystallographic characterization. As new methods for SEM crystallographic characterization are developed, however, these instruments will become increasingly powerful. Transmission electron microscopy will remain exceptionally useful for analyses that require very high resolution, but it is likely that SEM and EPMA will be used increasingly for a broader range of application that do not require submicron spatial resolution.

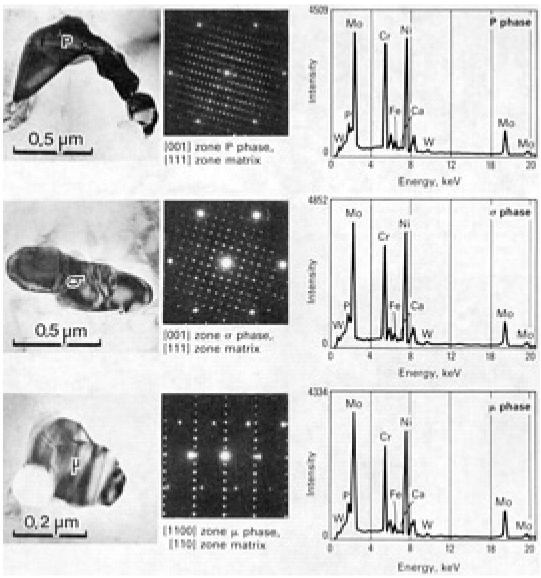
P
0.5 μm
[001] zone P phase,
[111] zone matrix
P phase
σ
0.5 μm
[001] zone σ phase,
[111] zone matrix
σ phase
μ
0.2 μm
[1100] zone μ phase,
[110] zone matrix
μ phase
Intensity
Mo
Cr
Ni
Fe
Ca
P
W
Energy, keV
0
4
8
12
16
20

Fig. 23 Combined TEM imaging, electron diffraction identification, and elemental microanalysis of P, σ, and μ intermetallic phases of alloy 22 weld metal. Source: Ref 3

Capabilities of Related Techniques

X-ray diffraction (XRD) provides faster and more precise crystallographic information, but averaged over bulk sample rather than corresponding to individual microstructural features.

Scanning Electron Microscopy (SEM). Sample preparation is much simpler. Scanning electron microscopy can characterize much larger samples and selected areas of interest. Imaging resolution is not as good as TEM. Spatial resolution for chemical analysis and crystallographic analysis is not as good as TEM. Scanning electron microscopy techniques for crystallographic analysis are not as mature as those for TEM.

Electron Probe Microanalysis (EPMA). Sample preparation is much simpler. Electron probe microanalysis can characterize much larger samples and selected areas of interest. Spatial resolution for chemical analysis is not as good as TEM, but counting statistics are much better, providing higher quality quantitative analyses.

Reference cited in this section

3. *Materials Characterization,* Vol 10, *ASM Handbook,* ASM International, 1986

References

1. J. Goldstein et al., *Scanning Electron Microscopy and Microanalysis,* 2nd ed., Plenum, 1992, p 85
2. B. Gabriel, *SEM: A User's Manual for Materials Science,* American Society for Metals, 1985, p 110
3. *Materials Characterization,* Vol 10, *ASM Handbook,* ASM International, 1986

Surface Analysis

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Introduction

A NUMBER OF METHODS can be used to obtain information about the chemistry of the first one to several atomic layers of samples of metals, as well as of other materials, such as semiconductors and various types of thin films. Of these methods, the scanning Auger microprobe is the most widely used. This instrument and method will be described in some detail, and the operation and capabilities of several other surface analysis methods will be more briefly described in comparison to it.

Scanning Auger Microprobe (SAM)

Capabilities

The scanning Auger microprobe is basically a scanning electron microscope (SEM) with two additional features:

- An Auger electron detector replaces an x-ray detector. The Auger detector is used to measure the energies of Auger electrons emitted from the sample. These characteristic energies enable identification of the elements present in the first few atomic layers of the surface. The concentrations of each element present can also be determined from the number of electrons detected at each characteristic energy. All elements except hydrogen and helium can be identified and analyzed in this way.
- An in situ ion milling capability provides for gradual removal of surface layers, thereby permitting depth profiling of elemental compositions within about 1 μm of the surface.

Typical Uses

These capabilities make the SAM well suited for the following types of applications:

- Identification and mapping of light elements (atomic numbers 3 to ~9) that are difficult to detect using SEM or electron probe microanalysis (EPMA)
- Elemental characterization of surface contaminants
- Depth profiling of elemental compositions within ~1 μm of the surface (this is particularly widely used in microelectronics applications)

Spatial Resolution

- Secondary electron imaging of surface topography: ~10 nm (same as SEM)
- Auger electron characterization of elemental chemistry: 10 to 20 nm; sampling depth: ~1 nm

Elemental Analysis Detection Threshold and Precision

- Threshold sensitivity: ~0.5%
- Precision of quantitative analyses: ~10% relative or 0.5% absolute, whichever is greater

Limitations

- Cannot detect hydrogen or helium
- Quantitative analyses are typically lower in quality than those of EPMA

Sample Requirements

- Samples up to ~2.5 cm diameter and 0.5 cm thick can be accommodated by most SAMs; larger samples can be accommodated in instruments designed for this purpose.
- Provisions must be made for charge to bleed off. Ideal samples are electrically conductive and must be free of fingerprints, oils, and other high vapor pressure materials.
- Flat samples are preferred, but rough samples can also be accommodated.

Operating Principles

Instrumentation. As noted above, the scanning Auger microprobe is essentially an SEM to which an Auger electron detector and an ion miller have been added (Fig. 1). An electron beam is produced and focused to a small spot on the sample surface. This spot can be rastered across an operator-defined area of the surface or stopped and moved to a particular location of interest. The beam penetrates the sample and interacts with the atoms in the first ~1 μm, exciting atoms and producing secondary electrons, exactly as was shown for the scanning electron microscope in Fig. 2-4 of the article "Microstructural Analysis." A secondary electron detector provides the capability to image the surface and locate areas of particular interest, as in a scanning electron microscope. However, the primary tool for chemical analysis is the Auger electron detector.

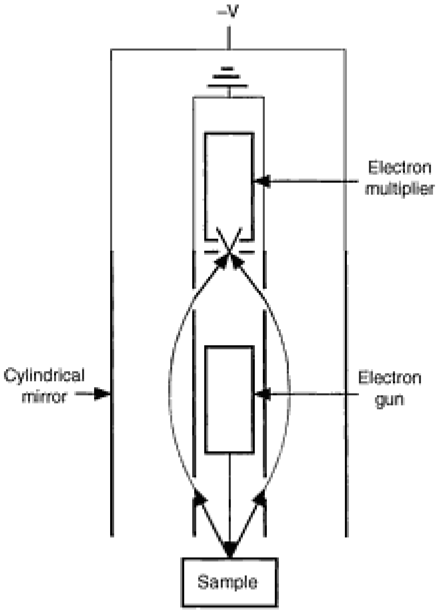
−V
Electron multiplier
Cylindrical mirror
Electron gun
Sample

Fig. 1 Schematic of a scanning Auger microprobe

Physical Basis. Auger electrons are emitted as the excited atoms relax. In a sense, they are the compliments of the characteristic x-rays that are used for chemical characterization in x-ray fluorescence (XRF), SEM, EPMA, and transmission electron microscopy (TEM). When atoms become excited by electrons being ejected from their inner shells, electrons from higher energy shells fill these vacated sites. This process always results in the release of energy equal to the energy difference between the donor and acceptor levels. For more information, see the section "X-Ray Fluorescence Spectroscopy" in the article "Bulk Elemental Analysis" in this Handbook. However, emission of characteristic x-rays is only one of the mechanisms by which this energy can be released. Another common mechanism is by the release of an Auger electron.

An Auger electron is an electron from one of the outer shells that is ejected from the atom with kinetic energy equal to the energy released by the relaxation event minus the energy required to remove the Auger electron from its orbit (Fig. 2). Because both energies associated with the relaxation events and the binding energies of the outer shell electrons provide characteristic "fingerprints" for each element, so do their differences, the energies of Auger electrons. Hence, the energies of Auger electrons can also be detected and used to identify which elements are in the portion of the sample being excited by the incident electron beam. These characteristic Auger electrons typically have energies of tens to thousands of electron volts.

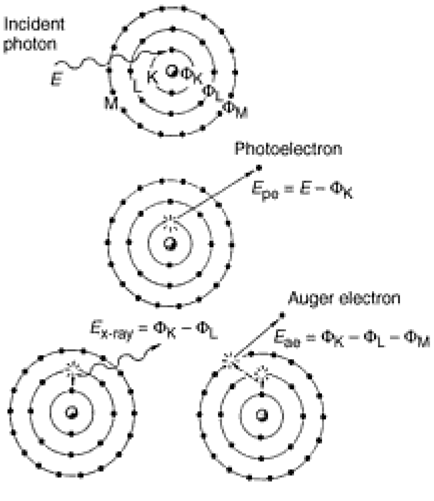
Incident photon
E
K
L
M
Φ_K
Φ_L
Φ_M
Photoelectron
$E_{pe} = E - \Phi_K$
$E_{x\text{-}ray} = \Phi_K - \Phi_L$
Auger electron
$E_{ae} = \Phi_K - \Phi_L - \Phi_M$

Fig. 2 Comparison of production of x-rays and Auger electrons. Source: Ref 1

The tendency for excited atoms to relax by Auger electron production versus x-ray photon emission increases with decreasing atomic number. Elements with atomic numbers less than ∼7 produce few characteristic x-rays but many Auger electrons (except for hydrogen and helium). As a result, SAM is commonly used for microstructural detection and quantification of such elements. Higher atomic number elements, however, produce more x-rays, so these elements are typically detected and quantified using SEM or EPMA. Although when analysis of the first few atomic layers is desired, SAM provides elemental analyses corresponding to this very near surface region.

While Auger electrons are generated throughout the beam-sample interaction volume, most of these dissipate some or all of their characteristic energies by interacting with the electrons belonging to other atoms in the sample. The only Auger electrons that escape the sample with their original characteristic energies are those generated within a few atom layers of the sample's surface. If the energies of all emitted electrons are detected and analyzed, then a graph similar to Fig. 3 is obtained. The lowest energy range is dominated by secondary electrons, the highest energy range is dominated by backscattered electrons, and the mid-energy range is dominated by Auger electrons, nearly all of which have had their characteristic energies reduced by interactions with the sample. But if Fig. 3 is examined closely, small signals can be found at particular energies. These represent the characteristic energies of the "undisturbed" Auger electrons that were generated by atoms at the surface or within a few atomic distances below the surface.

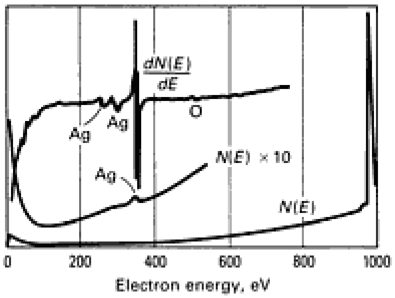

Fig. 3 Electron energy distribution from silver sample. Differentiated signal most clearly reveals the peak corresponding to Auger electrons that were produced very near the surface and exited the sample prior to interacting with other atoms. Source: Ref 2

Electron Collection and Energy Measurement. The energies of the emitted electrons are usually measured using a cylindrical "mirror" that has a variable negative potential applied to it, as shown in Fig. 1. As electrons enter the inlet aperture and pass though the analyzer chamber, the negative bias on the wall of the chamber repels them and causes them to travel in curved paths. The curvature of this path varies inversely with the kinetic energy of each electron; the paths of electrons with low kinetic energy are more easily deflected than those paths of electrons with high kinetic energy. This information provides a means of measuring the energy distribution of the electrons emitted from the sample. An electron detector is mounted near the exit aperture of the cylindrical mirror, and the negative bias applied to the mirror is gradually increased. The numbers of electrons entering the detector is counted as a function of mirror bias. This information enables the energy distribution of the electrons to be plotted.

The portion of the signal corresponding to the "undisturbed" Auger electrons is very small compared with the signal resulting from backscattered and Auger electrons whose energies have been reduced by interactions within the sample. This situation is typically overcome by differentiating the signal and plotting dN/dE versus E, as shown in Fig. 3. Because the Auger electrons typically originate in the outer electron shells, their energies are somewhat affected by bonding between atoms. These small energy shifts, which can frequently be discriminated by the energy analyzer, provide the ability to determine some information about the elements to which the atoms of interest are bonded.

Scanning Auger microprobe results are often presented as secondary electron images with accompanying Auger electron spectra identifying the elements present in particular features of interest. Low atomic number elements that cannot be detected by SEM and EPMA are readily detected in Auger spectra. Figure 4 provides an example of the use of Auger electrons to detect low atomic number elements with high spatial resolution.

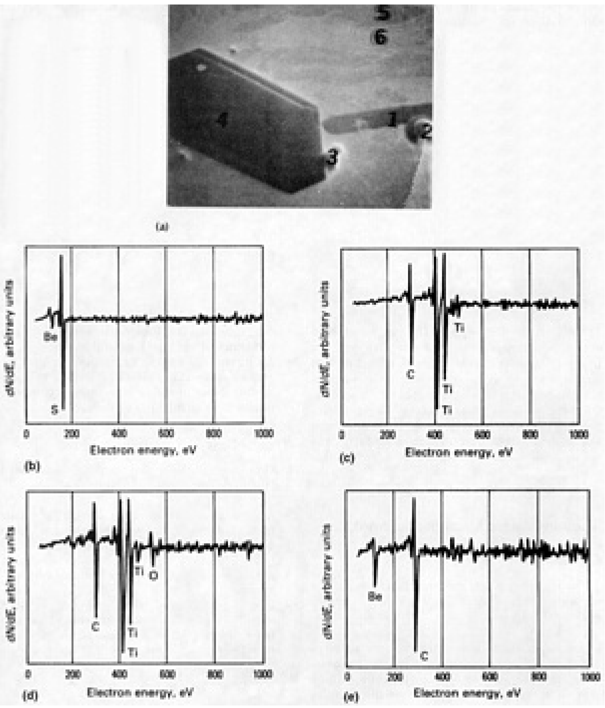

Fig. 4 Scanning Auger identification of elements, including some of low atomic number, present in several phases in a copper-beryllium alloy. (a) Secondary electron image showing inclusions. (b-e) Auger spectra obtained from the indicated microstructural features. (b) The long rod-shaped precipitate (point 1) is a beryllium sulfide. (c) The small round precipitate (point 2) is a titanium carbide. (d) The small irregular precipitate (point 3) is also a titanium carbide. (e) The large blocky angular precipitate (point 4) is a beryllium carbide. Source: Ref 2

Alternatively, the detector can be set to the energy associated with a particular element or compound of interest and the electron beam rastered over the surface, resulting in a map indicating the areas of high concentration of this material (Fig. 5).

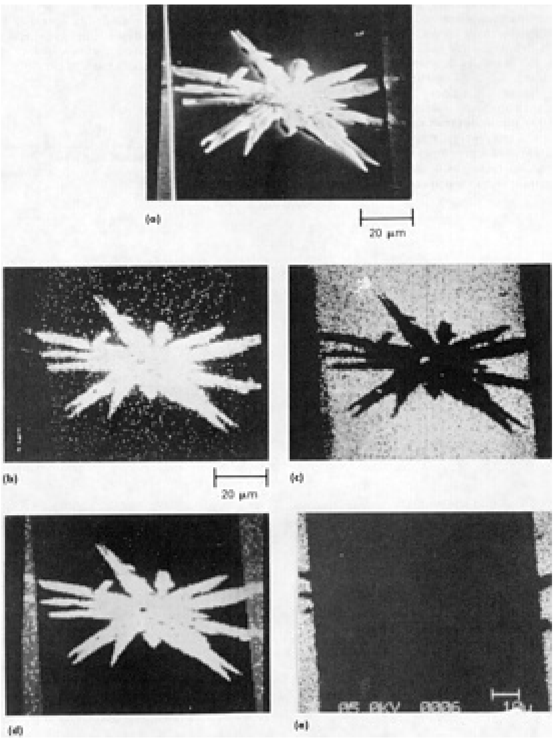

Fig. 5 Scanning Auger mapping of elements, including some of low atomic number, in a foreign particle on an integrated circuit. Note also the ability to distinguish between elemental silicon and silicon oxide due to bonding effects on Auger energies. (a) Secondary electron image of particle. (b-e) Auger maps showing locations of silicon oxide, elemental silicon, oxygen, and aluminum, respectively. Source: Ref 2

An ion sputtering gun is also incorporated into the chamber of the instrument and can be used to progressively remove thin layers of material from the surface of the sample. This removal provides the opportunity to perform Auger elemental measurements at various distances from the original sample surface. The practical limit of such depth profiling is $\sim$1 μm. An example of this depth profiling capability is shown in Fig. 6.

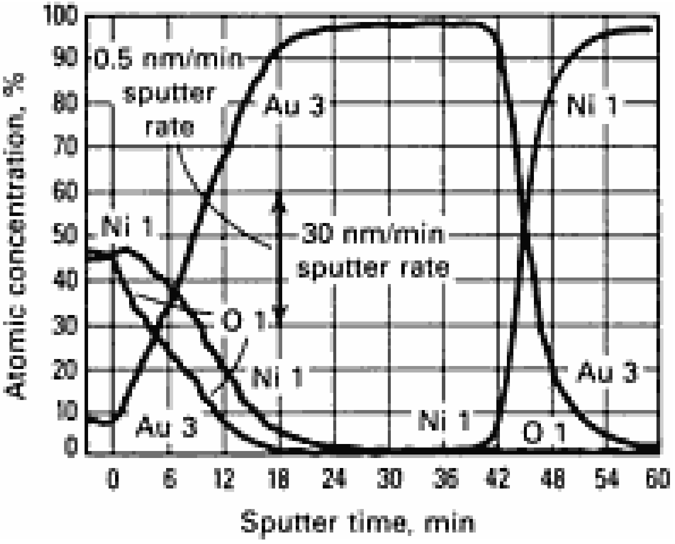

Fig. 6 Scanning Auger depth-composition profile obtained from a nickel-rich area of a gold-nickel-copper metallization surface. Source: Ref 2

References cited in this section

1. R. Jenkins, R. Gould, and D. Gedcke, *Quantitative X-Ray Spectrometry,* Dekker, 1981, p 16
2. *Materials Characterization,* Vol 10, *ASM Handbook,* ASM International, 1986

Related Surface Analysis Techniques

Non-Surface-Specific Methods

Scanning Electron Microscopy, Electron Probe Microanalysis (SEM, EPMA). These methods are better for combined imaging and elemental analysis of elements with higher atomic numbers. However, SEM and EPMA cannot readily analyze for low atomic number elements (less than $\sim$7 to 11), nor do they have either depth profiling capabilities or surface specific analytical capabilities.

Transmission electron microscopy (TEM) has better spatial resolution for imaging and chemical analysis, but an EDS system cannot readily analyze for low atomic number elements (below $\sim$7). The presence of lower atomic number elements can sometimes be inferred by electron diffraction if these elements are present in compounds that can be identified based on their interplanar spacings.

Surface-Specific Methods

A number of other techniques are frequently used to characterize the chemistries of the top one to five atomic layers of materials. While detailed descriptions of all of these methods are beyond the scope of this article, the following paragraphs provide brief summaries of two of the methods that are frequently used in metallurgical studies and comparisons of their capabilities with those of the scanning Auger microprobe.

Secondary ion mass spectroscopy (SIMS) directs a finely focused beam of energetic ions onto the sample surface, then it collects and analyzes the ionized atoms or clusters of atoms ejected from the sample surface by this beam. Information can be obtained with lateral spatial resolution of 100 to 500 nm. The ions removed from the surface are identified by a highly sensitive mass spectrometer. This identification provides for very sensitive detection of many elements, often in the parts per billion (ppb) range. In addition, it enables analysis for very low atomic number elements, including hydrogen. (SIMS is the only method able to detect hydrogen with microscopic spatial resolution.) The primary ion beam can be rastered over the surface, providing for high-sensitivity elemental mapping. Because it removes material from the surface, it also provides for depth profiling.

X-ray photoelectron spectroscopy (XPS) directs a single energy x-ray beam onto the surface. This beam penetrates 10 to 100 μm into the sample, interacting with atoms and ejecting photoelectrons from their inner shells. The energies of these photoelectrons are equal to the energy of the x-ray photons minus the characteristic electron binding energies. Many of the photoelectrons lose some or all of their energy in interactions with other atoms, but a few that are generated very close to the surface exit the sample undisturbed. The photoelectrons are collected and their energies analyzed using a device similar to the cylindrical mirror in a SAM. Analysis of the energies of the photoelectrons permits identification of the elements in the top few atomic layers. The excellent energy resolution of the analyzer enables it to discriminate the very small shifts in energy that result from bonding of the atoms of interest to other surrounding atoms. Hence, XPS is capable of providing information on surrounding atoms and chemical bonding. X-ray photoelectron spectroscopy does not utilize a fine incident beam; therefore, it does not provide images or chemical information with high lateral spatial resolution. It is generally not as sensitive as SIMS, but it is very useful for detecting some elements for which SIMS is not very sensitive. An ion sputtering capability is generally available to facilitate depth profiling. In general, XPS is most extensively used to obtain surface analyses with chemical bonding sensitivity.

References

1. R. Jenkins, R. Gould, and D. Gedcke, *Quantitative X-Ray Spectrometry,* Dekker, 1981, p 16
2. *Materials Characterization,* Vol 10, *ASM Handbook,* ASM International, 1986

Glossary of Metallurgical and Metalworking Terms

THIS GLOSSARY contains the definitions of some 3500 technical terms encountered in the metallurgical literature. The list includes terms from: general materials science, physical metallurgy, mechanical metallurgy, extractive metallurgy, melting and casting, forming and forging, powder metallurgy, heat treating, machining and grinding, welding and joining (brazing, soldering, and adhesive bonding), surface engineering (cleaning, finishing, and coating technology), corrosion and electrochemistry, tribology (wear, friction, and lubrication technology), fracture mechanics, mechanical testing, nondestructive testing and inspection, metallography, fractography, failure analysis, and materials characterization. These subject areas are representative of the topics covered in the 20-volume *ASM Handbook* series.

Many cross references to preferred terms, alternative terms, and closely related terms have been included; these cross references are printed in italics. Also, terms that are obsolete or otherwise inappropriate for use in current technical articles/reports, and so forth are so indicated. Many terms can have more than one meaning; alternative meanings are identified by parenthetical numbers preceding each alternative definition. Whenever possible, a general or generic meaning is given before a specific meaning, but there is no special significance to the order in which alternative meanings are given. In addition, many of the definitions in this glossary are compatible with (although not necessarily identical to) definitions published by ASTM, AWS, NACE, and other technical organizations.

Terms that are best defined using an accompanying figure are not included in this glossary. Examples here include weld joint configurations (e.g., tee joints, lap joints, etc.) and related nomenclature and cutting tool geometries (e.g., clearance angles, rake angles, etc.). These terms are defined and illustrated in the Sections "Joining" and "Machining," respectively, in this Handbook.

Although every effort has been made to provide as comprehensive a glossary as possible, space limitations dictate that only the most commonly used terms be defined. More specialized terms are defined in the many glossaries published throughout the *ASM Handbook* series and in the illustrated *ASM Materials Engineering Dictionary* published in 1992. The latter work also contains terms and definitions related to nonmetallic engineered materials and processing.

- **A**
- **abrasion**
  - (1) A process in which hard particles or protuberances are forced against and moved along a solid surface. (2) A roughening or scratching of a surface due to abrasive wear. (3) The process of grinding or wearing away through the use of abrasives.
- **abrasive**
  - (1) A hard substance used for grinding, honing, lapping, superfinishing, polishing, pressure blasting, or barrel finishing. Abrasives in common use are alumina, silicon carbide, boron carbide, diamond, cubic boron nitride, garnet, and quartz. (2) Hard particles, such as rocks, sand, or fragments of certain hard metals, that wear away a surface when they move across it under pressure. See also superabrasives .
- **abrasive belt**
  - A coated abrasive product, in the form of a belt, used in production grinding and polishing.
- **abrasive blasting**
  - A process for cleaning or finishing by means of an abrasive directed at high velocity against the workpiece.
- **abrasive disk**
  - (1) A grinding wheel that is mounted on a steel plate, with the exposed flat side being used for grinding. (2) A disk-shaped, coated abrasive product.
- **abrasive erosion**
  - Erosive wear caused by the relative motion of solid particles that are entrained in a fluid, moving nearly parallel to a solid surface. See also erosion .
- **abrasive flow machining**

    - Removal of material by a viscous, abrasive media flowing under pressure through or across a workpiece.
- **abrasive jet machining**
    - Material removal from a workpiece by impingement of fine abrasive particles that are entrained in a focused, high-velocity gas stream.
- **abrasive machining**
    - A machining process in which the points of abrasive particles are used as machining tools. Grinding is a typical abrasive machining process.
- **abrasive waterjet machining**
    - See waterjet/abrasive waterjet machining .
- **abrasive wear**
    - The removal of material from a surface when hard particles slide or roll across the surface under pressure. The particles may be loose or may be part of another surface in contact with the surface being abraded. Compare with adhesive wear .
- **abrasive wheel**
    - A grinding wheel composed of an abrasive grit and a bonding agent.
- **absolute density**
    - See density, absolute .
- **Ac_{cm}, Ac_1, Ac_3, Ac_4**
    - Defined under transformation temperature .
- **accelerated corrosion test**
    - Method designed to approximate, in a short time, the deteriorating effect under normal long-term service conditions.
- **accelerated-life test**
    - A method designed to approximate, in a short time, the deteriorating effect obtained under normal long-term service conditions. See also artificial aging .
- **accelerated testing**
    - A test performed on materials or assemblies that is meant to produce failures caused by the same failure mechanism as expected in field operation but in significantly shorter time. The failure mechanism is accelerated by changing one or more of the controlling test parameters.
- **acicular ferrite**
    - A highly substructured nonequiaxed ferrite formed upon continuous cooling by a mixed diffusion and shear mode of transformation that begins at a temperature slightly higher than the transformation temperature range for upper bainite. It is distinguished from bainite in that it has a limited amount of carbon available; thus, there is only a small amount of carbide present.
- **acicular ferrite steels**
    - Ultralow-carbon (<0.08%) steels having a microstructure consisting of either acicular ferrite (low-carbon bainite) or a mixture of acicular and equiaxed ferrite.
- **acid**
    - A chemical substance that yields hydrogen ions (H^+) when dissolved in water. Compare with base . (2) A term applied to slags, refractories, and minerals containing a high percentage of silica.
- **acid bottom and lining**
    - The inner bottom and lining of a melting furnace, consisting of materials like sand, siliceous rock, or silica brick that give an acid reaction at the operating temperature.
- **acid copper**
    - (1) Copper electrodeposited from an acid solution of a copper salt, usually copper sulfate. (2) The solution referred to in (1).
- **acid embrittlement**
    - A form of hydrogen embrittlement that may be induced in some metals by acid.
- **acid rain**
    - Atmospheric precipitation with a pH below 5.6 to 5.7. Burning of fossil fuels for heat and power is the major factor in the generation of oxides of nitrogen and sulfur, which are converted into nitric and sulfuric acids washed down in the rain. See also atmospheric corrosion .
- **acid refractory**
    - Siliceous ceramic materials of a high melting temperature, such as silica brick, used for metallurgical furnace linings. Compare with basic refractories .
- **acid steel**

  - Steel melted in a furnace with an acid bottom and lining and under a slag containing an excess of an acid substance such as silica.
- **acoustic emission**
  - A measure of integrity of a material, as determined by sound emission when a material is stressed. Ideally, emissions can be correlated with defects and/or incipient failure.
- **actinide metals**
  - The group of radioactive elements of atomic numbers 89 through 103 of the periodic system--namely, actinium, thorium, protactinium, uranium, neptunium, plutonium, americium, curium, berkelium, californium, einsteinium, fermium, mendelevium, nobelium, and lawrencium.
- **activated rosin flux**
  - A rosin-base flux containing an additive that increases wetting by the solder.
- **activation**
  - (1) The changing of a passive surface of a metal to a chemically active state. Contrast with passivation . (2) The (usually) chemical process of making a surface more receptive to bonding with a coating or an encapsulating material.
- **activation energy**
  - The energy required for initiating a metallurgical reaction--for example, plastic flow, diffusion, chemical reaction. The activation energy may be calculated from the slope of the line obtained by plotting the natural log of the reaction rate versus the reciprocal of the absolute temperature.
- **active**
  - The negative direction of electrode potential. Also used to describe corrosion and its associated potential range when an electrode potential is more negative than an adjacent depressed corrosion rate (passive) range.
- **active metal**
  - A metal ready to corrode or being corroded.
- **activity**
  - A measure of the chemical potential of a substance, where the chemical potential is not equal to concentration, that allows mathematical relations equivalent to those for ideal systems to be used to correlate changes in an experimentally measured quantity with changes in chemical potential.
- **addition agent**
  - (1) A substance added to a solution for the purpose of altering or controlling a process. Examples: wetting agents in acid pickles; brighteners or antipitting agents in plating solutions; inhibitors. (2) Any material added to a charge of molten metal in a bath or ladle to bring the alloy to specification.
- **adhesion**
  - (1) In frictional contacts, the attractive force between adjacent surfaces. In physical chemistry, adhesion denotes the attraction between a solid surface and a second (liquid or solid) phase. This definition is based on the assumption of a reversible equilibrium. In mechanical technology, adhesion is generally irreversible. In railway engineering, adhesion often means friction. (2) Force of attraction between the molecules (or atoms) of two different phases. Contrast with cohesion . (3) The state in which two surfaces are held together by interfacial forces, which may consist of valence forces, interlocking action, or both.
- **adhesive**
  - A substance capable of holding materials together by surface attachment. Adhesive is a general term and includes, among others, cement, glue, mucilage, and paste.
- **adhesive bonding**
  - A materials joining process in which an adhesive, placed between the faying surfaces (adherends), solidifies to produce an adhesive bond.
- **adhesive wear**
  - (1) Wear by transference of material from one surface to another during relative motion due to a process of solid-phase welding. Particles that are removed from one surface are either permanently or temporarily attached to the other surface. (2) Wear due to localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or loss from either surface. Compare with abrasive wear .
- **adjustable bed**
  - Bed of a press designed so that the die space height can be varied conveniently.
- **Ae_{cm}, Ae_1, Ae_3, Ae_4**
  - Defined under transformation temperature .

- **age hardening**
  - Hardening by aging (heat treatment) usually after rapid cooling or cold working.
- **age softening**
  - Spontaneous decrease of strength and hardness that takes place at room temperature in certain strain hardened alloys, especially those of aluminum.
- **aging**
  - (1) The effect on materials of exposure to an environment for a prolonged interval of time. (2) The process of exposing materials to an environment for a prolonged interval of time in order to predict in-service lifetime.
- **aging (heat treatment)**
  - A change in the properties of certain metals and alloys that occurs at ambient or moderately elevated temperatures after hot working or a heat treatment (quench aging in ferrous alloys, natural or artificial aging in ferrous and nonferrous alloys) or after a cold-working operation (strain aging). The change in properties is often, but not always, due to a phase change (precipitation), but never involves a change in chemical composition of the metal or alloy. See also age hardening , artificial aging , interrupted aging , natural aging , overaging , precipitation hardening , precipitation heat treatment , progressive aging , quench aging , step aging , and strain aging .
- **air acetylene welding**
  - A fuel gas welding process in which coalescence is produced by heating with a gas flame or flames obtained from the combustion of acetylene with air, without the application of pressure, and with or without the use of filler metal.
- **air bend die**
  - Angle-forming dies in which the metal is formed without striking the bottom of the die. Metal contact is made at only three points in the cross section: the nose of the male die and the two edges of a V-shape die opening.
- **air bending**
  - Bending in an air bend die .
- **air carbon arc cutting**
  - An arc cutting process in which metals to be cut are melted by the heat of a carbon arc and the molten metal is removed by a blast of air.
- **air classification**
  - The separation of metal powder into particle-size fractions by means of an air stream of controlled velocity; an application of the principle of elutriation .
- **air-hardening steel**
  - A steel containing sufficient carbon and other alloying elements to harden fully during cooling in air or other gaseous media from a temperature above its transformation range. The term should be restricted to steels that are capable of being hardened by cooling in air in fairly large sections, about 50 mm (2 in.) or more in diameter. Same as self-hardening steel.
- **air-lift hammer**
  - A type of gravity-drop hammer in which the ram is raised for each stroke by an air cylinder. Because length of stroke can be controlled, ram velocity and therefore the energy delivered to the workpiece can be varied. See also drop hammer and gravity hammer .
- **alclad**
  - Composite wrought product comprised of an aluminum alloy core having one or both surfaces a metallurgically bonded aluminum or aluminum alloy coating that is anodic to the core and thus electrochemically protects the core against corrosion.
- **alkali metal**
  - A metal in group IA of the periodic system--namely, lithium, sodium, potassium, rubidium, cesium, and francium. They form strongly alkaline hydroxides, hence the name.
- **alkaline cleaner**
  - A material blended from alkali hydroxides and such alkaline salts as borates, carbonates, phosphates, or silicates. The cleaning action may be enhanced by the addition of surface-active agents and special solvents.
- **alkaline earth metal**
  - A metal in group IIA of the periodic system--namely, beryllium, magnesium, calcium, strontium, barium, and radium--so called because the oxides or "earths" of calcium, strontium, and barium were found by the early chemists to be alkaline in reaction.

- **alligatoring**
  - (1) Pronounced wide cracking over the entire surface of a coating having the appearance of alligator hide. (2) The longitudinal splitting of flat slabs in a plane parallel to the rolled surface. Also called fish-mouthing.
- **alligator skin**
  - See orange peel .
- **allotriomorphic crystal**
  - A crystal whose lattice structure is normal but whose external surfaces are not bounded by regular crystal faces; rather, the external surfaces are impressed by contact with other crystals or another surface such as a mold wall, or are irregularly shaped because of nonuniform growth. Compare with idiomorphic crystal .
- **allotropy**
  - (1) A near synonym for polymorphism . Allotropy is generally restricted to describing polymorphic behavior in elements, terminal phases, and alloys whose behavior closely parallels that of the predominant constituent element. (2) The existence of a substance, especially an element, in two or more physical states (for example, crystals).
- **allowance**
  - (1) The specified difference in limiting sizes (minimum clearance or maximum interference) between mating parts, as computed arithmetically from the specified dimensions and tolerances of each part. (2) In a foundry, the specified clearance. The difference in limiting sizes, such as minimum clearance or maximum interference between mating parts, as computed arithmetically. See also tolerance .
- **alloy**
  - (1) A substance having metallic properties and being composed of two or more chemical elements of which at least one is a metal. (2) To make or melt an alloy.
- **alloy cast iron**
  - Highly alloyed cast irons containing more than 3% alloy content. Alloy cast irons may be of a type of white iron, gray iron, or ductile iron.
- **alloying element**
  - An element added to and remaining in a metal that changes structure and properties.
- **alloy plating**
  - The codeposition of two or more metallic elements.
- **alloy powder, alloyed powder**
  - A metal powder consisting of at least two constituents that are partially or completely alloyed with each other.
- **alloy steel**
  - Steel containing specified quantities of alloying elements (other than carbon and the commonly accepted amounts of manganese, copper, silicon, sulfur, and phosphorus) within the limits recognized for constructional alloy steels, added to effect changes in mechanical or physical properties.
- **alloy system**
  - A complete series of compositions produced by mixing in all proportions any group of two or more components, at least one of which is a metal.
- **all-weld-metal test specimen**
  - A test specimen wherein the portion being tested is composed wholly of weld metal.
- **alpha brass**
  - A solid-solution phase of one or more alloying elements in copper having the same crystal lattice as copper.
- **alpha ferrite**
  - See ferrite .
- **alpha iron**
  - The body-centered cubic form of pure iron, stable below 910 °C (1670 °F).
- **alternate immersion test**
  - A corrosion test in which the specimens are intermittently exposed to a liquid medium at definite time intervals.
- **aluminizing**
  - Forming of an aluminum or aluminum alloy coating on a metal by hot dipping, hot spraying, or diffusion.

- **amalgam**
    - A dental alloy produced by combining mercury with alloy particles of silver, tin, copper, and sometimes zinc.
- **amorphous**
    - Not having a crystal structure; noncrystalline.
- **amorphous solid**
    - A rigid material whose structure lacks crystalline periodicity; that is, the pattern of its constituent atoms or molecules does not repeat periodically in three dimensions. See also metallic glass .
- **anelastic deformation**
    - Any portion of the total deformation of a body that occurs as a function of time when load is applied and which disappears completely after a period of time when the load is removed.
- **anelasticity**
    - The property of solids by virtue of which strain is not a single-value function of stress in the low-stress range where no permanent set occurs.
- **angle of bite**
    - In the rolling of metals, the location where all of the force is transmitted through the rolls; the maximum attainable angle between the roll radius at the first contact and the line of roll centers. Operating angles less than the angle of bite are termed contact angles or rolling angles.
- **angle of nip**
    - In rolling, the angle of bite. In roll, jaw, or gyratory crushing, the entrance angle formed by the tangents at the two points of contact between the working surfaces and the (assumed) spherical particles to be crushed.
- **angstrom (unit)**
    - A unit of linear measure equal to 10^{-10} m, or 0.1 nm (nanometer), sometimes used to express small distances such as interatomic distances and some wavelengths.
- **anion**
    - A negatively charged ion that migrates through the electrolyte toward the anode under the influence of a potential gradient. See also cation and ion .
- **anisotropy**
    - The characteristic of exhibiting different values of a property in different directions with respect to a fixed reference system in the material.
- **annealing**
    - A generic term denoting a treatment consisting of heating to and holding at a suitable temperature followed by cooling at a suitable rate, used primarily to soften metallic materials, but also to simultaneously produce desired changes in other properties or in microstructure. The purpose of such changes may be, but is not confined to: improvement of machinability, facilitation of cold work, improvement of mechanical or electrical properties, and/or increase in stability of dimensions. When the term is used unqualifiedly, full annealing is implied. When applied only for the relief of stress, the process is properly called stress relieving or stress-relief annealing.

      In ferrous alloys, annealing usually is done above the upper critical temperature, but the time-temperature cycles vary widely both in maximum temperature attained and in cooling rate employed, depending on composition, material condition, and results desired. When applicable, the following commercial process names should be used: black annealing, blue annealing, box annealing, bright annealing, cycle annealing, flame annealing, full annealing, graphitizing, in-process annealing, isothermal annealing, malleabilizing, orientation annealing, process annealing, quench annealing, spheroidizing, subcritical annealing.

      In nonferrous alloys, annealing cycles are designed to: (a) remove part or all of the effects of cold working (recrystallization may or may not be involved); (b) cause substantially complete coalescence of precipitates from solid solution in relatively coarse form; or (c) both, depending on composition and material condition. Specific process names in commercial use are final annealing, full annealing, intermediate annealing, partial annealing, recrystallization annealing, stress-relief annealing, anneal to temper.

- **annealing carbon**
    - See temper carbon .
- **annealing twin**

  - A twin formed in a crystal during recrystallization.
- **anneal to temper**
  - A final partial anneal that softens a cold-worked nonferrous alloy to a specified level of hardness or tensile strength.
- **anode**
  - (1) The electrode of an electrolyte cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. It is usually at the electrode that corrosion occurs and metal ions enter solution. (2) The positive (electron-deficient) electrode in an electrochemical circuit. Contrast with cathode .
- **anode copper**
  - Special-shaped copper slabs, resulting from the refinement of blister copper in a reverberatory furnace, used as anodes in electrolytic refinement.
- **anode effect**
  - The effect produced by polarization of the anode in electrolysis. It is characterized by a sudden increase in voltage and a corresponding decrease in amperage due to the anode becoming virtually separated from the electrolyte by a gas film.
- **anode efficiency**
  - Current efficiency at the anode .
- **anode film**
  - (1) The portion of solution in immediate contact with the anode, especially if the concentration gradient is steep. (2) The outer layer of the anode itself.
- **anode polarization**
  - See polarization .
- **anodic cleaning**
  - Electrolytic cleaning in which the work is the anode. Also called reverse-current cleaning.
- **anodic coating**
  - A film on a metal surface resulting from an electrolytic treatment at the anode.
- **anodic pickling**
  - Electrolytic pickling in which the work is the anode.
- **anodic polarization**
  - The change of the electrode potential in the noble (positive) direction due to current flow. See also polarization .
- **anodic protection**
  - (1) A technique to reduce the corrosion rate of a metal by polarizing it into its passive region, where dissolution rates are low. (2) Imposing an external electrical potential to protect a metal from corrosive attack. (Applicable only to metals that show active-passive behavior.) Contrast with cathodic protection .
- **anodic reaction**
  - Electrode reaction equivalent to a transfer of positive charge from the electronic to the ionic conductor. An anodic reaction is an oxidation process. An example common in corrosion is $M(s) \rightarrow M(aq)^{2+} + 2e^{-}$.
- **anodizing**
  - Forming a conversion coating on a metal surface by anodic oxidation; most frequently applied to aluminum.
- **anolyte**
  - The electrolyte adjacent to the anode in an electrolytic cell.
- **antiferromagnetic material**
  - A material wherein interatomic forces hold the elementary atomic magnets (electron spins) of a solid in alignment, a state similar to that of a ferromagnetic material but with the difference that equals numbers of elementary magnets (spins) face in opposite directions and are antiparallel, causing the solid to be weakly magnetic, that is, paramagnetic, instead of ferromagnetic.
- **antifriction material**
  - A material that exhibits low-friction or self-lubricating properties.
- **antipitting agent**
  - An addition agent for electroplating solutions to prevent the formation of pits or large pores in the electrodeposit.
- **anvil**

  - A large, heavy metal block that supports the frame structure and holds the stationary die of a forging hammer. Also, the metal block on which blacksmith forgings are made.
- **anvil cap**
  - Same as sow block .
- **apparent density**
  - (1) The weight per unit volume of a powder, in contrast to the weight per unit volume of the individual particles. (2) The weight per unit volume of a porous solid, where the unit volume is determined from external dimensions of the mass. Apparent density is always less than the true density of the material itself.
- **Ar_{cm}, Ar_1, Ar_3, Ar_4, Ar', Ar''**
  - Defined under transformation temperature .
- **arbor**
  - (1) In machine grinding, the spindle on which the wheel is mounted. (2) In machine cutting, a shaft or bar for holding and driving the cutter. (3) In founding, a metal shape embedded in green sand or dry sand cores to support the sand or the applied load during casting.
- **arbor press**
  - A machine used for forcing arbors or mandrels into drilled or bored parts preparatory to turning or grinding. Also used for forcing bushings, shafts, or pins into or out of holes.
- **arbor-type cutter**
  - A cutter having a hole for mounting on an arbor and usually having a keyway for a driving key.
- **arc**
  - A luminous discharge of electrical current crossing the gap between two electrodes.
- **arc blow**
  - The deflection of an electric arc from its normal path because of magnetic forces.
- **arc brazing**
  - A brazing process in which the heat required is obtained from an electric arc.
- **arc cutting**
  - A group of cutting processes that melt the metals to be cut with the heat of an arc between an electrode and the base metal. See carbon arc cutting , metal arc cutting , gas metal arc cutting , gas tungsten arc cutting , plasma arc cutting , and air carbon arc cutting . Compare with oxygen arc cutting .
- **arc furnace**
  - A furnace in which metal is melted either directly by an electric arc between an electrode and the work or indirectly by an arc between two electrodes adjacent to the metal.
- **arc gouging**
  - An arc cutting process variation used to form a bevel or groove.
- **arc melting**
  - Melting metal in an electric arc furnace.
- **arc oxygen cutting**
  - See preferred term oxygen arc cutting .
- **arc plasma**
  - See plasma arc cutting .
- **arc seam weld**
  - A seam weld make by an arc welding process.
- **arc spot weld**
  - A spot weld made by an arc welding process.
- **arc spraying (ASP)**
  - A thermal spraying process using an arc between two consumable electrodes of surfacing materials as a heat source and a compressed gas to atomize and propel the surfacing material to the substrate.
- **arc strike**
  - A discontinuity consisting of any localized remelted metal, heat-affected metal, or change in the surface profile of any part of a weld or base metal resulting from an arc.
- **arc welding**
  - A group of welding processes that produce coalescence of metals by heating them with an arc, with or without the application of pressure, and with or without the use of filler metal.
- **arc welding electrode**

  - See electrode (welding) .
- **argon oxygen decarburization (AOD)**
  - A secondary refining process for the controlled oxidation of carbon in a steel melt. In the AOD process, oxygen, argon, and nitrogen are injected into a molten metal bath through submerged, side-mounted tuyeres.
- **artifact**
  - A feature of artificial character, such as a scratch or a piece of dust on a metallographic specimen, that can be erroneously interpreted as a real feature.
- **artificial aging**
  - Aging above room temperature. See aging (heat treatment) . Compare with natural aging .
- **as-cast condition**
  - Castings as removed from the mold without subsequent heat treatment.
- **as-welded**
  - The condition of weld metal, welded joints, and weldments after welding, but prior to any subsequent thermal, mechanical, or chemical treatments.
- **athermal transformation**
  - A reaction that proceeds without benefit of thermal fluctuations--that is, thermal activation is not required. Such reactions are diffusionless and can take place with great speed when the driving force is sufficiently high. For example, many martensitic transformations occur athermally on cooling, even at relatively low temperatures, because of the progressively increasing drive force. In contrast, a reaction that occurs at constant temperature is an isothermal transformation; thermal activation is necessary in this case and the reaction proceeds as a function of time.
- **atmospheric corrosion**
  - The gradual degradation or alteration of a material by contact with substances present in the atmosphere, such as oxygen, carbon dioxide, water vapor, and sulfur and chlorine compounds.
- **atmospheric riser**
  - A riser that uses atmospheric pressure to aid feeding. Essentially, a blind riser into which a small core or rod protrudes; the function of the core or rod is to provide an open passage so that the molten interior of the riser will not be under a partial vacuum when metal is withdrawn to feed the casting but will always be under atmospheric pressure.
- **atomic number (*Z*)**
  - The number of protons in an atomic nucleus, which determines the individuality of the atom as a chemical element.
- **atomic percent**
  - The number of atoms of an element in a total of 100 representative atoms of a substance.
- **atomization**
  - The disintegration of a molten metal into particles by a rapidly moving gas or liquid stream or by other means.
- **attritious wear**
  - Wear of abrasive grains in grinding such that the sharp edges gradually become rounded. A grinding wheel that has undergone such wear usually has a glazed appearance.
- **attritor**
  - A high-intensity ball mill whose drum is stationary and whose balls are agitated by rotating baffles, paddles, or rods at right angle to the drum axis.
- **attritor grinding**
  - The intensive grinding or alloying in an attritor. Examples: milling of carbides and binder metal powders and mechanical alloying of hard dispersoid particles with softer metal or alloy powders. See also mechanical alloying .
- **Auger electron**
  - An electron emitted from an atom with a vacancy in an inner shell. Auger electrons have a characteristic energy detected as peaks in the energy spectra of the secondary electrons generated.
- **Auger electron spectroscopy (AES)**
  - A technique for chemical analysis of surface layers that identifies the atoms present in a layer by measuring the characteristic energies of their Auger electrons.
- **ausforming**
  - Thermomechanical treatment of steel in the metastable austenitic condition below the recrystallization temperature followed by quenching to obtain martensite and/or bainite.

- **austempered ductile iron**
  - A moderately alloyed ductile iron that is austempered for high strength with appreciable ductility. See also austempering .
- **austempering**
  - A heat treatment for ferrous alloys in which a part is quenched from the austenitizing temperature at a rate fast enough to avoid formation of ferrite or pearlite and then held at a temperature just above M_s until transformation to bainite is complete. Although designated as bainite in both austempered steel and austempered ductile iron (ADI), austempered steel consists of two phase mixtures containing ferrite and carbide, while austempered ductile iron consists of two phase mixtures containing ferrite and austenite.
- **austenite**
  - A solid solution of one or more elements in face-centered cubic iron (gamma iron). Unless otherwise designated (such as nickel austenite), the solute is generally assumed to be carbon.
- **austenitic grain size**
  - The size attained by the grains in steel when heated to the austenitic region. This may be revealed by appropriate etching of cross sections after cooling to room temperature.
- **austenitic manganese steel**
  - A wear-resistant material containing about 1.2% C and 12% Mn. Used primarily in the fields of earthmoving, mining, quarrying, railroading, ore processing, lumbering, and in the manufacture of cement and clay products. Also known as Hadfield steel.
- **austenitic steel**
  - An alloy steel whose structure is normally austenitic at room temperature.
- **austenitizing**
  - Forming austenite by heating a ferrous alloy into the transformation range (partial austenitizing) or above the transformation range (complete austenitizing). When used without qualification, the term implies complete austenitizing.
- **autogenous weld**
  - A fusion weld made without the addition of filler metal.
- **automatic press**
  - A press in which the work is fed mechanically through the press in synchronism with the press action. An automation press is an automatic press that, in addition, is provided with built-in electrical and pneumatic control equipment.
- **automatic welding**
  - Welding with equipment that performs the welding operation without adjustment of the controls by a welding operator. The equipment may or may not load and unload the workpieces. Contrast with machine welding .
- **auxiliary anode**
  - In electroplating, a supplementary anode positioned so as to raise the current density on a certain area of the cathode and thus obtain better distribution of plating.
- **auxiliary electrode**
  - An electrode commonly used in polarization studies to pass current to or from a test electrode. It is usually made from a noncorroding material.
- **axial rolls**
  - In ring rolling, vertically displaceable, taped rolls mounted in a horizontally displaceable frame opposite to, but on the same centerline as, the main roll and rolling mandrel. The axial rolls control ring height during rolling.
- **B**
- **Babbitt metal**
  - A nonferrous bearing alloy originated by Isaac Babbitt in 1839. Currently, the term includes several tin-base alloys consisting mainly of various amounts of copper, antimony, tin, and lead. Lead-base Babbitt metals are also used.
- **back draft**
  - A reverse taper on a casting pattern or a forging die that prevents the pattern or forged stock from being removed from the cavity.
- **backfire**
  - The momentary recession of the flame into the welding tip or cutting tip followed by immediate reappearance or complete extinction of the flame. See also flashback .
- **back gouging**

  - The removal of weld metal and base metal from the other side of a partially welded joint to facilitate complete fusion and complete joint penetration upon subsequent welding from that side.
- **backing**
  - (1) In grinding, the material (paper, cloth, or fiber) that serves as the base for coated abrasives. (2) In welding, a material placed under or behind a joint to enhance the quality of the weld at the root. It may be a metal backing ring or strip; a pass of weld metal; or a nonmetal such as carbon, granular flux, or a protective gas. (3) In plain bearings, that part of the bearing to which the bearing alloy is attached, normally by a metallurgical bond.
- **backoff**
  - A rapid withdrawal of a grinding wheel or cutting tool from contact with a workpiece.
- **backward extrusion**
  - Same as indirect extrusion . See extrusion .
- **bainite**
  - A metastable aggregate of ferrite and cementite resulting from the transformation of austenite at temperatures below the pearlite range but above M_s, the martensite start temperature. Upper bainite is an aggregate that contains parallel lath-shape units of ferrite, produces the so-called "feathery" appearance in optical microscopy, and is formed above approximately 350 °C (660 °F). Lower bainite, which has an acicular appearance similar to tempered martensite, is formed below approximately 350 °C (660 °F).
- **bainitic hardening**
  - Quench-hardening treatment resulting principally in the formation of bainite.
- **Bakelite**
  - A proprietary name for a phenolic thermosetting resin used as a plastic mounting material for metallographic samples.
- **baking**
  - (1) Heating to a low temperature in order to remove gases. (2) Curing or hardening surface coatings such as paints by exposure to heat. (3) Heating to drive off moisture, as in baking of sand cores after molding.
- **ball burnishing**
  - (1) Same as ball sizing . (2) Removing burrs and polishing small stampings and small machined parts by tumbling in the presence of metal balls.
- **ball mill**
  - A machine consisting of a rotating hollow cylinder partly filled with metal balls (usually hardened steel or white cast iron) or sometimes pebbles; used to pulverize crushed ores or other substances such as pigments or ceramics.
- **ball milling**
  - A method of grinding and mixing material, with or without liquid, in a rotating cylinder or conical mill partially filled with grinding media such as balls or pebbles.
- **ball sizing**
  - Sizing and finishing a hole by forcing a ball of suitable size, finish, and hardness through the hole or by using a burnishing bar or broach consisting of a series of spherical lands of gradually increasing size coaxially arranged. Also called ball burnishing , and sometimes ball broaching.
- **banded structure**
  - A segregated structure consisting of alternating nearly parallel bands of different composition, typically aligned in the direction of primary hot working.
- **banding**
  - Inhomogeneous distribution of alloying elements or phases aligned in filaments or plates parallel to the direction of working. See also banded structure , ferrite-pearlite banding , and segregation banding .
- **band mark**
  - An indentation in carbon steel or strip caused by external pressure on the packaging band around cut lengths or coils; it may occur in handling, transit, or storage.
- **bands**
  - Hot-rolled steel strip, usually produced for rerolling into thinner sheet or strip. Also known as hot bands or band steel.
- **bar**
  - (1) A section hot rolled from a billet to a form, such as round, hexagonal, octagonal, square, or rectangular, with sharp or rounded corners or edges and a cross-sectional area of less than 105

cm^2 (16 in.^{2}). (2) A solid section that is long in relationship to its cross-sectional dimensions, having a completely symmetrical cross section and a width or greatest distance between parallel faces of 9.5 mm ($\frac{3}{8}$ in.) or more. (3) An obsolete unit of pressure equal to 100 kPa.

- **bare electrode**
  - A filler metal electrode consisting of a single metal or alloy that has been produced into a wire, strip, or bar form and that has had no coating or covering applied to it other than that which was incidental to its manufacture or preservation.
- **bar folder**
  - A machine in which a folding bar or wing is used to bend a metal sheet whose edge is clamped between the upper folding leaf and the lower stationary jaw into a narrow, sharp, close, and accurate fold along the edge. It is also capable of making rounded folds such as those used in wiring. A universal folder is more versatile in that it is limited to width only by the dimensions of the sheet.
- **Barkhausen effect**
  - The sequence of abrupt changes in magnetic induction occurring when the magnetizing force acting on a ferromagnetic specimen is varied.
- **barrel cleaning**
  - Mechanical or electrolytic cleaning of metal in rotating equipment.
- **barrel finishing**
  - Improving the surface finish of workpieces by processing them in rotating equipment along with abrasive particles that may be suspended in a liquid. The barrel is normally loaded about 60% full with a mixture of parts, media, compound, and water.
- **barreling**
  - Convexity of the surfaces of cylindrical or conical bodies, often produced unintentionally during upsetting or as a natural consequence during compression testing.
- **barrel plating**
  - Plating articles in a rotating container, usually a perforated cylinder that operates at least partially submerged in a solution.
- **barstock**
  - Same as bar .
- **base**
  - (1) A chemical substance that yields hydroxyl ions (OH) when dissolved in water. Compare with acid . (2) The surface on which a single-point tool rests when held in a tool post. Also known as heel. (3) In forging, see anvil .
- **base metal**
  - (1) The metal present in the largest proportion in an alloy; brass, for example, is a copper-base alloy. (2) The metal to be brazed, cut, soldered, or welded. (3) After welding, that part of the metal that was not melted. (4) A metal that readily oxidizes or that dissolves to form ions. Contrast with noble metal (2) .
- **basic bottom and lining**
  - The inner bottom and lining of a melting furnace, consisting of materials such as crushed burned dolomite, magnesite, magnesite bricks, or basic slag that give a basic reaction at the operating temperature.
- **basic oxygen furnace**
  - A large tiltable vessel lined with basic refractory material that is a type of furnace for modern steelmaking. After the furnace is charged with molten pig iron (which usually comprises 65 to 75% of the charge), scrap steel, and fluxes, a lance is brought down near the surface of the molten metal and a jet of high-velocity oxygen impinges on the metal. The oxygen reacts with carbon and other impurities in the steel to form liquid compounds that dissolve in the slag and gases that escape from the top of the vessel.
- **basic refractories**
  - Refractories whose major constituent is lime, magnesia, or both, and which may react chemically with acid refractories, acid slags, or acid fluxes at high temperatures. Basic refractories are used for furnace linings. Compare with acid refractory .
- **basic steel**
  - Steel melted in a furnace with a basic bottom and lining and under a slag containing an excess of a basic substance such as magnesia or lime.

- **basis metal**
    - See preferred term substrate .
- **batch**
    - A quantity of materials formed during the same process or in one continuous process and having identical characteristics throughout. See also lot .
- **batch furnace**
    - A furnace used to heat treat a single load at a time. Batch-type furnaces are necessary for large parts such as heavy forgings and are preferred for complex alloy grades requiring long cycles.
- **Bauschinger effect**
    - The phenomenon by which plastic deformation increases yield strength in the direction of plastic flow and decreases it in other directions.
- **bauxite**
    - A whitish to reddish mineral composed largely of hydrates of alumina having a composition of $Al_2O_3 \cdot 2H_2O$. It is the most important ore (source) of aluminum, alumina abrasives, and alumina-base refractories.
- **Bayer process**
    - A process for extracting alumina from bauxite ore before the electrolytic reduction. The bauxite is digested in a solution of sodium hydroxide, which converts the alumina to soluble aluminate. After the "red mud" residue has been filtered out, aluminum hydroxide is precipitated, filtered out, and calcined to alumina.
- **beach marks**
    - Macroscopic progression marks on a fatigue fracture or stress-corrosion cracking surface that indicate successive positions of the advancing crack front. The classic appearance is of irregular elliptical or semielliptical rings, radiating outward from one or more origins. Beach marks (also known as clamshell marks or arrest marks) are typically found on service fractures where the part is loaded randomly, intermittently, or with periodic variations in mean stress or alternating stress. See also striation .
- **bead**
    - (1) Half-round cavity in a mold, or half-round projection or molding on a casting. (2) A single deposit of weld metal produced by fusion.
- **beaded flange**
    - A flange reinforced by a low ridge, used mostly around a hole.
- **beading**
    - Raising a ridge or projection on sheet metal.
- **bead weld**
    - See preferred term surfacing weld .
- **bearing strength**
    - The maximum bearing stress that can be sustained. Also, the bearing stress at that point on the stress-strain curve at which the tangent is equal to the bearing stress divided by n% of the bearing hole diameter.
- **bearing stress**
    - The shear load on a mechanical joint (such as a pinned or riveted joint) divided by the effective bearing area. The effective bearing area of a riveted joint, for example, is the sum of the diameters of all rivets times the thickness of the loaded member.
- **bearing test**
    - A method of determining the response to stress (load) of sheet products that are subjected to riveting, bolting, or a similar fastening procedure. The purpose of the test is to determine the bearing strength of the material and to measure the bearing stress versus the deformation of the hole created by a pin or rod of circular cross section that pierces the sheet perpendicular to the surface.
- **bed**
    - (1) The stationary portion of a press structure that usually rests on the floor or foundation, forming the support for the remaining parts of the press and the pressing load. The bolster and sometimes the lower die are mounted on the top surface of the bed. (2) For machine tools, the portion of the main frame that supports the tool, the work, or both. (3) Stationary part of the shear frame that supports the material being sheared and the fixed blade.
- **Beilby layer**

    - A layer of metal disturbed by mechanical working, wear, or mechanical polishing presumed to be without regular crystalline structure (amorphous); originally applied to grain boundaries.
- **belt furnace**
    - A continuous-type furnace that uses a mesh-type or cast-link belt to carry parts through the furnace.
- **belt grinding**
    - Grinding with an abrasive belt.
- **bench molding**
    - Casting sand molds by hand tamping loose or production patterns at a bench without the assistance of air or hydraulic action.
- **bend allowance**
    - The length of the arc of the neutral axis between the tangent points of a bend.
- **bend angle**
    - The angle through which a bending operation is performed, that is, the supplementary angle to that formed by the two bend tangent lines or planes.
- **bending**
    - The straining of material, usually flat sheet or strip metal, by moving it around a straight axis lying in the neutral plane. Metal flow takes place within the plastic range of the metal, so that the bent part retains a permanent set after removal of the applied stress. The cross section of the bend inward from the neutral plane is in compression; the rest of the bend is in tension.
- **bending brake**
    - A form of open-frame single-action press that is comparatively wide between the housings, with a bed designed for holding long, narrow forming edges or dies. Used for bending and forming strip, plate, and sheet (into boxes, panels, roof decks, and so on). Also known as press brake .
- **bending dies**
    - Dies used in presses for bending sheet metal or wire parts into various shapes. The work is done by the punch pushing the stock into cavities or depressions of similar shape in the die or by auxiliary attachments operated by the descending punch.
- **bending moment**
    - The algebraic sum of the couples or the moments of the external forces, or both, to the left or right of any section on a member subjected to bending by couples or transverse forces, or both.
- **bending rolls**
    - Various types of machinery equipped with two or more rolls to form curved sheet and sections.
- **bend or twist (defect)**
    - Distortion similar to warpage generally caused during forging or trimming operations. When the distortion is along the length of the part, it is termed bend; when across the width, it is termed twist. When bend or twist exceeds tolerance, it is considered a defect. Corrective action consists of hand straightening, machine straightening, or cold restriking.
- **bend radius**
    - (1) The inside radius of a bend section. (2) The radius of a tool around which metal is bent during fabrication.
- **bend tangent**
    - A tangent point at which a bending arc ceases or changes.
- **bend test**
    - A test for determining relative ductility of metal that is to be formed (usually sheet, strip, plate, or wire) and for determining soundness and toughness of metal (after welding, for example). The specimen is usually bent over a specified diameter through a specified angle for a specified number of cycles.
- **beneficiation**
    - Concentration or other preparation of ore for smelting.
- **bentonite**
    - A colloidal claylike substance derived from the decomposition of volcanic ash composed chiefly of the minerals of the montmorillonite family. It is used for bonding molding sand.
- **Bessemer process**
    - A process for making steel by blowing air through molten pig iron contained in a refractory lined vessel so as to remove by oxidation most of the carbon, silicon, and manganese. This process is essentially obsolete in the United States.
- **beta (β) ray**

    - A ray of electrons emitted during the spontaneous disintegration of certain atomic nuclei.
- **beta (β) structure**
    - A Hume-Rothery designation for structurally analogous body-centered cubic phases (similar to β brass) or electron compounds that have ratios of three valence electrons to two atoms. Not to be confused with a β phase on a phase diagram.
- **bevel**
    - An angular edge preparation in a weld member.
- **bevel flanging**
    - Same as flaring .
- **biaxiality**
    - In a biaxial stress state, the ratio of the smaller to the larger principal stress.
- **biaxial stress**
    - A state of stress in which only one of the principal stresses is zero, the other two usually being in tension.
- **billet**
    - (1) A semifinished section that is hot rolled from a metal ingot, with a rectangular cross section usually ranging from 105 to 230 cm^2 (16 to 36 in.^2), the width being less than twice the thickness. Where the cross section exceeds 230 cm^2 (36 in.^2), the term bloom is properly but not universally used. Sizes smaller than 105 cm^2 (16 in.^2) are usually termed bars. (2) A solid semifinished round or square product that has been hot worked by forging, rolling, or extrusion. See also bar .
- **billet mill**
    - A primary rolling mill used for making steel billets.
- **binary alloy**
    - An alloy containing only two component elements.
- **binary system**
    - The complete series of compositions produced by mixing a pair of components in all proportions.
- **binder**
    - (1) In founding, a material, other than water, added to foundry sand to bind the particles together, sometimes with the use of heat. (2) In powder technology, a cementing medium: either a material added to the powder to increase the green strength of the compact, which is expelled during sintering; or a material (usually of relatively low melting point) added to a powder mixture for the specific purpose of cementing together powder particles that alone would not sinter into a strong body.
- **binder metal**
    - A metal used as a binder. An example would be cobalt in cemented carbides.
- **biological corrosion**
    - Deterioration of metals as a result of the metabolic activity of microorganisms. Also known as biofouling.
- **bipolar electrode**
    - An electrode in an electrolytic cell that is not mechanically connected to the power supply, but is so placed in the electrolyte, between the anode and cathode, that the part nearer the anode becomes cathodic and the part nearer the cathode becomes anodic. Also called intermediate electrode.
- **bipolar field**
    - A longitudinal magnetic field that creates two magnetic poles within a piece of material. Compare with circular field .
- **black annealing**
    - Box annealing or pot annealing ferrous alloy sheet, strip, or wire impart a black color to the oxidized surface. See also box annealing .
- **blackheart malleable**
    - See malleable iron .
- **blacking**
    - Carbonaceous materials, such as graphite or powdered carbon, usually mixed with a binder and frequently carried in suspension in water or other liquid used as a thin facing applied to surfaces of molds or cores to improve casting finish.
- **black oxide**
    - A black finish on a metal produced by immersing it in hot oxidizing salts or salt solutions.

- **blank**
  - (1) In forming, a piece of sheet metal, produced in cutting dies, that is usually subjected to further press operations. (2) A pressed, presintered, or fully sintered powder metallurgy compact, usually in the unfinished condition and requiring cutting, machining, or some other operation to produce the final shape. (3) A piece of stock from which a forging is made, often called a slug or multiple .
- **blank carburizing**
  - Simulating the carburizing operation without introducing carbon. This is usually accomplished by using an inert material in place of the carburizing agent, or by applying a suitable protective coating to the ferrous alloy.
- **blankholder**
  - (1) The part of a drawing or forming die that holds the workpiece against the draw ring to control metal flow. (2) The part of a drawing or forming die that restrains the movement of the workpiece to avoid wrinkling or tearing of the metal.
- **blanking**
  - The operation of punching, cutting, or shearing a piece out of stock to a predetermined shape.
- **blank nitriding**
  - Simulating the nitriding operation without introducing nitrogen. This is usually accomplished by using an inert material in place of the nitriding agent or by applying a suitable protective coating to the ferrous alloy.
- **blast furnace**
  - A shaft furnace in which solid fuel is burned with an air blast to smelt ore in a continuous operation. Where the temperature must be high, as in the production of pig iron, the air is preheated. Where the temperature can be lower, as in smelting of copper, lead, and tin ores, a smaller furnace is economical, and preheating of the blast is not required.
- **blasting or blast cleaning**
  - A process for cleaning or finishing metal objects with an air blast or centrifugal wheel that throws abrasive particles against the surface of the workpiece. Small, irregular particles of metal are used as the abrasive in gritblasting; sand, in sandblasting; and steel, in shotblasting.
- **blended sand**
  - A mixture of sands of different grain size and clay content that provides suitable characteristics for foundry use.
- **blending**
  - In powder metallurgy, the thorough intermingling of powders of the same nominal composition (not to be confused with mixing).
- **blind riser**
  - A riser that does not extend through the top of the mold.
- **blister**
  - (1) A casting defect, on or near the surface of the metal, resulting from the expansion of gas in a subsurface zone. It is characterized by a smooth bump on the surface of the casting and a hole inside the casting directly below the bump. (2) A raised area, often dome shaped, resulting from loss of adhesion between a coating or deposit and the substrate.
- **blister copper**
  - An impure intermediate product in the refining of copper, produced by blowing copper matte in a converter, the name being derived from the large blisters on the cast surface that result from the liberation of SO_2 and other gases.
- **block**
  - A preliminary forging operation that roughly distributes metal preparatory for finish.
- **block and finish**
  - The forging operation in which a part to be forged is blocked and finished in one heat through the use of tooling having both a block impression and a finish impression in the same die block.
- **blocker**
  - The impression in the dies (often one of a series of impressions in a single die set) that imparts to the forging an intermediate shape, preparatory to forging of the final shape. Also called blocking impression.
- **blocker dies**
  - Forging dies having generous contours, large radii, draft angles of 7° or more, and liberal finish allowances. See also finish allowance .

- **blocker-type forging**
  - A forging that approximates the general shape of the final part with relatively generous finish allowance and radii. Such forgings are sometimes specified to reduce die costs where only a small number of forgings are described and the cost of machining each part to its final shape is not excessive.
- **blocking**
  - In forging, a preliminary operation performed in closed dies, usually hot, to position metal properly so that in the finish operation the dies will be filled correctly. Blocking can ensure proper working of the material and can increase die life.
- **blocking impression**
  - Same as blocker .
- **bloom**
  - (1) A semifinished hot-rolled product, rectangular in cross section, produced on a blooming mill. See also billet . For steel, the width of a bloom is not more than twice the thickness, and the cross-sectional area is usually not less than about 230 cm^2 (36 $in.^2$). Steel blooms are sometimes made by forging. (2) A visible exudation or efflorescence on the surface of an electroplating bath. (3) A bluish fluorescent cast to a painted surface caused by deposition of a thin film of smoke, dust, or oil. (4) A loose, flowerlike corrosion product that forms when certain metals are exposed to a moist environment.
- **blooming mill**
  - A primary rolling mill used to make blooms.
- **blowhole**
  - A hole in a casting or a weld caused by gas entrapped during solidification. See also porosity .
- **blue annealing**
  - Heating hot-rolled ferrous sheet in an open furnace to a temperature within the transformation range, then cooling in air to soften the metal. A bluish oxide surface layer forms.
- **blue brittleness**
  - Brittleness exhibited by some steels after being heated to some temperature within the range of about 205 to 370 °C (400 to 700 °F), particularly if the steel is worked at the elevated temperature. Killed steels are virtually free of this kind of brittleness.
- **bluing**
  - Subjecting the scale-free surface of a ferrous alloy to the action of air, steam, or other agents at a suitable temperature, thus forming a thin blue film of oxide and improving the appearance and resistance to corrosion. This term is ordinarily applied to sheet, strip, or finished parts. It is used also to denote the heating of springs after fabrication to improve their properties.
- **board hammer**
  - A type of forging hammer in which the upper die and ram are attached to "boards" that are raised to the striking position by power-driven rollers and let fall by gravity. See also gravity hammer .
- **bolster**
  - A plate to which dies may be fastened, the assembly being secured to the top surface of a press bed. In mechanical forging, such a plate is also attached to the ram .
- **bond**
  - (1) In grinding wheels and other relatively rigid abrasive products, the material that holds the abrasive grains together. (2) In welding, brazing, or soldering, the junction of joined parts. Where filler metal is used, it is the junction of the fused metal and the heat-affected base metal. (3) In an adhesive-bonded or diffusion-bonded joint, the line along which the faying surfaces are joined together. (4) In thermal spraying, the junction between the material deposited and the substrate, or its strength.
- **book mold**
  - A split permanent mold hinged like a book.
- **bore**
  - A hole or cylindrical cavity produced by a single-point or multipoint tool other than a drill.
- **boriding**
  - Thermochemical treatment involving the enrichment of the surface layer of an object with borides. This surface-hardening process is performed below the Ac_1 temperature. Also referred to as boronizing.
- **boring**

  - Enlarging a hole by removing metal with a single- or occasionally a multiple-point cutting tool moving parallel to the axis of rotation of the work or tool.
- **bort**
  - (1) Natural diamond of a quality not suitable for gem use. (2) Industrial diamond.
- **bosh**
  - (1) The section of a blast furnace extending upward from the tuyeres to the plane of maximum diameter. (2) A lining of quartz that builds up during the smelting of copper ores and that decreases the diameter of the furnace at the tuyeres. (3) A tank, often with sloping sides, used for washing metal parts or for holding cleaned parts.
- **boss**
  - A relatively short protrusion or projection from the surface of a forging or casting, often cylindrical in shape. Usually intended for drilling and tapping for attaching parts.
- **bottom board**
  - In casting, a flat base for holding the flask in making sand molds.
- **bottom drill**
  - A flat-ended twist drill used to convert a cone at the bottom of a drilled hole into a cylinder.
- **bottoming tap**
  - A tap with a chamfer of 1 to 1$\frac{1}{2}$ threads in length.
- **bottom pipe**
  - An oxide-lined fold or cavity at the butt end of a slab, bloom, or billet; formed by folding the end of an ingot over on itself during primary rolling. Bottom pipe is not pipe, in that it is not a shrinkage cavity, and in that sense, the term is a misnomer. Bottom pipe is similar to extrusion pipe. It is normally discarded when the slab, bloom, or billet is cropped following primary reduction.
- **bowing**
  - Deviation from flatness.
- **box annealing**
  - Annealing a metal or alloy in a sealed container under conditions that minimize oxidation. In box annealing a ferrous alloy, the charge is usually heated slowly to a temperature below the transformation range, but sometimes above or within it, and is then cooled slowly; this process is also called close annealing or pot annealing. See also black annealing .
- **boxing**
  - The continuation of a fillet weld around a corner of a member as an extension of the principal weld.
- **brake**
  - A device for bending sheet metal to a desired angle.
- **brale indenter**
  - A conical 120° diamond indenter with a conical tip (a 0.2 mm tip radius is typical) used in certain types of Rockwell and scratch hardness tests.
- **brass**
  - A copper-zinc alloy containing up to 40% Zn, to which smaller amounts of other elements may be added.
- **braze**
  - A weld produced by heating an assembly to suitable temperatures and by using a filler metal having a liquidus above 450 °C (840 °F) and below the solidus of the base metal. The filler metal is distributed between the closely fitted faying surfaces of the joint by capillary action.
- **brazeability**
  - The capacity of a metal to be brazed under the fabrication conditions imposed into a specific suitably designed structure and to perform satisfactorily in the intended service.
- **braze welding**
  - A method of welding by using a filler metal having a liquidus above 450 °C (840 °F) and below the solidus of the base metals. Unlike brazing, in braze welding, the filler metal is not distributed in the joint by capillary attraction.
- **brazing**
  - A group of welding processes that join solid materials together by heating them to a suitable temperature and using a filler metal having a liquidus above 450 °C (840 °F) and below the

solidus of the base materials. The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction.

- **brazing alloy**
  - See preferred term brazing filler metal .
- **brazing filler metal**
  - (1) The metal that fills the capillary gap and has a liquidus above 450 °C (840 °F) but below the solidus of the base materials. (2) A nonferrous filler metal used in brazing and braze welding.
- **brazing sheet**
  - Brazing filler metal in sheet form.
- **breakdown**
  - (1) An initial rolling or drawing operation, or a series of such operations, for the purpose of reducing a casting or extruded shape prior to the finish reduction to desired size. (2) A preliminary press-forging operation.
- **breaking stress**
  - Same as fracture stress (1) .
- **breaks**
  - Creases or ridges usually in "untempered" or in aged material where the yield point has been exceeded. Depending on the origin of the breaks, they may be termed cross breaks , coil breaks , edge breaks, or sticker breaks .
- **bridge die**
  - A two-section extrusion die capable of producing tubing or intricate hollow shapes without the use of a separate mandrel. Metal separates into two streams as it is extruded past a bridge section, which is attached to the main die section and holds a stub mandrel in the die opening; the metal then is rewelded by extrusion pressure before it enters the die opening.
- **bridging**
  - (1) Premature solidification of metal across a mold section before the metal below or beyond solidifies. (2) Solidification of slag within a cupola at or just above the tuyeres. (3) Welding or mechanical locking of the charge in a downfeed melting or smelting furnace. (4) In powder metallurgy, the formation of arched cavities in a powder mass. (5) In soldering, an unintended solder connection between two or more conductors, either securely or by mere contact. Also called a crossed joint or solder short.
- **bright annealing**
  - Annealing in a protective medium to prevent discoloration of the bright surface.
- **bright dip**
  - A solution that produces, through chemical action, a bright surface on an immersed metal.
- **brightener**
  - An agent or combination of agents added to an electroplating bath to produce a lustrous deposit.
- **bright finish**
  - A high-quality finish produced on ground and polished rolls. Suitable for electroplating.
- **bright nitriding**
  - Nitriding in a protective medium to prevent discoloration of the bright surface. Compare with blank nitriding .
- **bright plate**
  - An electrodeposit that is lustrous in the as-plated condition.
- **Brinell hardness number (HB)**
  - A number related to the applied load and to the surface area of the permanent impression made by a ball indenter computed from:

$$\mathrm{HB} = 0.012 \times \frac{2F}{D(D - \sqrt{D^2 - d^2})}$$

  - where *F* is the test force, N; *D* is diameter of ball, mm; and *d* is mean diameter of the impression, mm.
- **Brinell hardness test**

  - A test for determining the hardness of a material by forcing a hard steel or carbide ball of specified diameter (typically, 10 mm) into it under a specified load. The result is expressed as the Brinell hardness number.
- **brinelling**
  - (1) Indentation of the surface of a solid body by repeated local impact or impacts, or static overload. Brinelling may occur especially in a rolling-element bearing. (2) Damage to a solid bearing surface characterized by one or more plastically formed indentations brought about by overload. See also false brinelling .
- **brine quenching**
  - A quench in which brine (salt water-chlorides, carbonates, and cyanides) is the quenching medium. The salt addition improves the efficiency of water at the vapor phase or hot stage of the quenching process.
- **brittle crack propagation**
  - A very sudden propagation of a crack with the absorption of no energy except that stored elastically in the body. Microscopic examination may reveal some deformation even though it is not noticeable to the unaided eye. Contrast with ductile crack propagation .
- **brittle fracture**
  - Separation of a solid accompanied by little or no macroscopic plastic deformation. Typically, brittle fracture occurs by rapid crack propagation with less expenditure of energy than for ductile fracture. Brittle tensile fractures have a bright, granular appearance and exhibit little or no necking. A chevron pattern may be present on the fracture surface, pointing toward the origin of the crack, especially in brittle fractures in flat platelike components. Examples of brittle fracture include transgranular cracking (cleavage and quasi-cleavage fracture) and intergranular cracking (decohesive rupture).
- **brittleness**
  - The tendency of a material to fracture without first undergoing significant plastic deformation. Contrast with ductility .
- **broaching**
  - Cutting with a tool that consists of a bar having a single edge or a series of cutting edges (i.e., teeth) on its surface. The cutting edges of multiple-tooth, or successive single-tooth, broaches increase in size and/or change in shape. The broach cuts in a straight line or axial direction when relative motion is produced in relation to the workpiece, which may also be rotating. The entire cut is made in single or multiple passes over the workpiece to shape the required surface contour.
- **bronze**
  - A copper-rich copper-tin alloy with or without small proportions of other elements such as zinc and phosphorus. By extension, certain copper-base alloys containing considerably less tin than other alloying elements, such as manganese bronze (copper-zinc plus manganese, tin, and iron) and leaded tin bronze (copper-lead plus tin and sometimes zinc). Also, certain other essentially binary copper-base alloys containing no tin, such as aluminum bronze (copper-aluminum), silicon bronze (copper-silicon), and beryllium bronze (copper-beryllium). Also, trade designations for certain specific copper-base alloys that are actually brasses, such as architectural bronzes (57 Cu, 40 Zn, 3 Pb) and commercial bronze (90 Cu, 10 Zn).
- **bronzing**
  - (1) Applying a chemical finish to copper or copper-alloy surfaces to alter the color. (2) Plating a copper-tin alloy on various materials.
- **brush anodizing**
  - An anodizing process similar to brush plating .
- **brush plating**
  - Plating with a concentrated solution or gel held in or fed to an absorbing medium, pad, or brush carrying the anode (usually insoluble). The brush is moved back and forth over the area of the cathode to be plated.
- **buckle**
  - (1) Bulging of a large, flat face of a casting; in investment casting, caused by dip coat peeling from the pattern. (2) An indentation in a casting, resulting from expansion of the sand, can be termed the start of an expansion defect. (3) A local waviness in metal bar or sheet, usually transverse to the direction of rolling.
- **buckling**

    - (1) A mode of failure generally characterized by an unstable lateral material deflection due to compressive action on the structural element involved. (2) In metal forming, a bulge, bend, kink, or other wavy condition of the workpiece caused by compressive stresses. See also compressive stress .
- **buffer**
    - (1) A substance that by its addition or presence tends to minimize the physical and chemical effects of one or more of the substances in a mixture. Properties often buffered include pH, oxidation potential, and flame or plasma temperatures. (2) A substance whose purpose is to maintain a constant hydrogen-ion concentration in water solutions, even where acids or alkalis are added. Each buffer has a characteristic limited range of pH over which it is effective.
- **buffing**
    - Developing a lustrous surface by contacting the work with a rotating buffing wheel.
- **buffing wheel**
    - Buff sections assembled to the required face width for use on a rotating shaft between flanges. Sometimes called a buff.
- **buildup**
    - (1) A weld surfacing variation in which surfacing metal is deposited to achieve the required dimensions. See also buttering . (2) Excessive electrodeposition that occurs on high-current-density areas, such as corners or edges.
- **built-up edge**
    - (1) Chip material adhering to the tool face adjacent to the cutting edge during cutting. (2) Material from the workpiece, especially in machining, which is stationary with respect to the tool.
- **bulging**
    - (1) Expanding the walls of a cup, shell, or tube with an internally expanded segmented punch or a punch composed of air, liquids, or semiliquids such as waxes, rubber, and other elastomers. (2) The process of increasing the diameter of a cylindrical shell (usually to a spherical shape) or of expanding the outer walls of any shell or box shape whose walls were previously straight.
- **bulk forming**
    - Forming processes, such as extrusion, forging, rolling, and drawing, in which the input material is in billet, rod, or slab form and a considerable increase in surface-to-volume ratio in the formed part occurs under the action of largely compressive loading. Compare with sheet forming .
- **bulk modulus of elasticity (*K*)**
    - The measure of resistance to change in volume; the ratio of hydrostatic stress to the corresponding unit change in volume. This elastic constant can be expressed by:

$$K = \frac{\sigma_m}{\Delta V} = \frac{-p}{\Delta V} = \frac{1}{\beta}$$

    - where K is the bulk modulus of elasticity, σ_m is hydrostatic or mean stress tensor, p is hydrostatic pressure, and β is compressibility. Also known as bulk modulus, compression modulus, hydrostatic modulus, and volumetric modulus of elasticity.
- **bull block**
    - A machine with a power-driven revolving drum for cold drawing wire through a drawing die as the wire winds around the drum.
- **bulldozer**
    - Slow-acting horizontal mechanical press with a large bed used for bending and straightening. The work is done between dies and can be performed hot or cold. The machine is closely allied to a forging machine.
- **bullion**
    - (1) A semirefined alloy containing sufficient precious metal to make recovery profitable. (2) Refined gold or silver, uncoined.
- **bull's-eye structure**
    - The microstructure of malleable or ductile cast iron when graphite nodules are surrounded by a ferrite layer in a pearlitic matrix.
- **bumper**

  - A machine used for packing molding sand in a flask by repeated jarring or jolting. See also jolt ramming .
- **bumping**
  - (1) Forming a dish in metal by means of many repeated blows. (2) Forming a head. (3) Setting the seams on sheet metal parts. (4) Ramming sand in a flask by repeated jarring and jolting.
- **burned deposit**
  - A dull, nodular electrodeposit resulting from excessive plating current density.
- **burned-in sand**
  - A defect consisting of a mixture of sand and metal cohering to the surface of a casting.
- **burned-on sand**
  - A mixture of sand and cast metal adhering to the surface of a casting. In some instances, may resemble metal penetration .
- **burned plating**
  - See burned deposit .
- **burning**
  - (1) Permanently damaging a metal or alloy by heating to cause either incipient melting or intergranular oxidation. See also overheating . (2) During subcritical annealing, particularly in continuous annealing, production of a severely decarburized and grain-coarsened surface layer that results from excessively prolonged heating to an excessively high temperature. (3) In grinding, getting the work hot enough to cause discoloration or to change the microstructure by tempering or hardening. (4) In sliding contacts, the oxidation of a surface due to local heating in an oxidizing environment.
- **burnishing**
  - Finish sizing and smooth finishing of surfaces (previously machined or ground) by displacement, rather than removal, of minute surface irregularities with smooth-point or line-contact fixed or rotating tools.
- **burnoff**
  - (1) Unintentional removal of an autocatalytic deposit from a nonconducting substrate, during subsequent electroplating operations, owing to the application of excessive current or a poor contact area. (2) Removal of volatile lubricants such as metallic stearates from metal powder compacts by heating immediately prior to sintering.
- **burr**
  - (1) A thin ridge or roughness left on a workpiece (e.g., forgings or sheet metal blanks) resulting from cutting, punching, or grinding. (2) A rotary tool having teeth similar to those on hand files.
- **burring**
  - Same as deburring .
- **bushing**
  - A bearing or guide.
- **buster**
  - A pair of shaped dies used to combine preliminary forging operations, such as edging and blocking, or to loosen scale.
- **butler finish**
  - A semilustrous metal finish composed of fine, uniformly distributed parallel lines, usually produced with a soft abrasive buffing wheel; similar in appearance to the traditional hand-rubbed finish on silver.
- **buttering**
  - A form of surfacing in which one or more layers of weld metal are deposited on the groove face of one member (for example, a high-alloy weld deposit on steel base metal that is to be welded to a dissimilar base metal). The buttering provides a suitable transition weld deposit for subsequent completion of the butt weld (joint).
- **button**
  - (1) A globule of metal remaining in an assaying crucible or cupel after fusion has been completed. (2) That part of a weld that tears out in destructive testing of a spot, seam, or projection welded specimen.
- **C**
- **cake**
  - (1) A copper or copper alloy casting, rectangular in cross section, used for rolling into sheet or strip. (2) A coalesced mass of unpressed metal powder.

- **calcination**
  - Heating ores, concentrates, precipitates, or residues to decompose carbonates, hydrates, or other compounds.
- **calomel electrode**
  - (1) An electrode widely used as a reference electrode of known potential in electrometric measurement of acidity and alkalinity, corrosion studies, voltammetry, and measurement of the potentials of other electrodes. (2) A secondary reference electrode of the composition: Pt/Hg-Hg_2Cl_2/KCl solution. For 1.0 *N* KCl solution, its potential versus a hydrogen electrode at 25 °C (77 °F) and one atmosphere is +0.281 V.
- **calorizing**
  - Imparting resistance to oxidation to an iron or steel surface by heating in aluminum powder at 800 to 1000 °C (1470 to 1830 °F).
- **camber**
  - (1) Deviation from edge straightness, usually referring to the greatest deviation of side edge from a straight line. (2) The tendency of material being sheared from sheet to bend away from the sheet in the same plane. (3) Sometimes used to denote crown in rolls where the center diameter has been increased to compensate for deflection caused by the rolling pressure. (4) The planar deflection of a flat cable or flexible laminate from a straight line of specified length. A flat cable or flexible laminate with camber is similar to the curve of an unbanked race track.
- **cam press**
  - A mechanical forming press in which one or more of the slides are operated by cams; usually a double-action press in which the blankholder slide is operated by cams through which the dwell is obtained.
- **can**
  - A sheathing of soft metal that encloses a sintered metal billet for the purpose of hot working (hot isostatic pressing, hot extrusion) without undue oxidation.
- **canning**
  - (1) A dished distortion in a flat or nearly flat sheet metal surface, sometimes referred to as oil canning. (2) Enclosing a highly reactive metal within a relatively inert material for the purpose of hot working without undue oxidation of the active metal.
- **capillary action**
  - (1) The phenomenon of intrusion of a liquid into interconnected small voids, pores, and channels in a solid, resulting from surface tension. (2) The force by which liquid, in contact with a solid, is distributed between closely fitted faying surfaces of the joint to be brazed or soldered.
- **capillary attraction**
  - (1) The combined force of adhesion and cohesion that causes liquids, including molten metals, to flow between very closely spaced and solid surfaces, even against gravity. (2) In powder metallurgy, the driving force for the infiltration of the pores of a sintered compact by a liquid.
- **capped steel**
  - A type of steel similar to rimmed steel, usually cast in a bottle-top ingot mold, in which the application of a mechanical or a chemical cap renders the rimming action incomplete by causing the top metal to solidify. The surface condition of capped steel is much like that of rimmed steel, but certain other characteristics are intermediate between those of rimmed steel and those of semikilled steel .
- **capping**
  - Partial or complete separation of a powder metallurgy compact into two or more portions by cracks that originate near the edges of the punch faces and that proceed diagonally into the compact.
- **carbide**
  - A compound of carbon with one or more metallic elements.
- **carbide tools**
  - Cutting or forming tools, usually made from tungsten, titanium, tantalum, or niobium carbides, or a combination of them, in a matrix of cobalt, nickel, or other metals. Carbide tools are characterized by high hardnesses and compressive strengths and may be coated to improve wear resistance. See also cemented carbide .
- **carbon arc cutting**
  - An arc cutting process in which metals are severed by melting them with the heat of an arc between a carbon electrode and the base metal.

- **carbon arc welding**
  - An arc welding process that produces coalescence of metals by heating them with an arc between a carbon electrode and the work. No shielding is used. Pressure and filler metal may or may not be used.
- **carbon edges**
  - Carbonaceous deposits in a wavy pattern along the edges of a steel sheet or strip; also known as snaky edges.
- **carbon electrode**
  - A nonfiller material electrode used in arc welding or cutting, consisting of a carbon or graphite rod, which may be coated with copper or other coatings.
- **carbon equivalent**
  - (1) For cast iron, an empirical relationship of the total carbon, silicon, and phosphorus contents expressed by the formula:

    $$CE = \%C + 0.3(\%Si) + 0.33(\%P) - 0.027(\%Mn) + 0.4(\%S)$$

  - (2) For rating of weldability:

    $$CE = C + \frac{Mn}{6} + \frac{Ni}{15} + \frac{Cu}{15} + \frac{Cr}{5} + \frac{Mo}{5} + \frac{V}{5}$$

- **carbonitriding**
  - A case-hardening process in which a suitable ferrous material is heated above the lower transformation temperature in a gaseous atmosphere of such composition as to cause simultaneous absorption of carbon and nitrogen by the surface and, by diffusion, create a concentration gradient. The heat-treating process is completed by cooling at a rate that produces the desired properties in the workpiece.
- **carbonization**
  - The high-temperature conversion of an organic substance into elemental carbon. Should not be confused with *carbur*ization.
- **carbonizing flame**
  - See preferred term reducing flame .
- **carbon potential**
  - A measure of the ability of an environment containing active carbon to alter or maintain, under prescribed conditions, the carbon level of a steel. In any particular environment, the carbon level attained will depend on such factors as temperature, time, and steel composition.
- **carbon steel**
  - Steel having no specified minimum quantity for any alloying element--other than the commonly accepted amounts of manganese (1.65%), silicon (0.60%), and copper (0.60%)--and containing only an incidental amount of any element other than carbon, silicon, manganese, copper, sulfur, and phosphorus. Low-carbon steels contain up to 0.30% C, medium-carbon steels contain from 0.30 to 0.60% C, and high-carbon steels contain from 0.60 to 1.00% C.
- **carbonyl powder**
  - Metal powders prepared by the thermal decomposition of a metal carbonyl compound such as nickel tetracarbonyl $Ni(CO)_4$ or iron pentacarbonyl $Fe(CO)_5$. See also thermal decomposition .
- **carburizing**
  - Absorption and diffusion of carbon into solid ferrous alloys by heating, to a temperature usually above Ac_3, in contact with a suitable carbonaceous material. A form of case hardening that produces a carbon gradient extending inward from the surface, enabling the surface layer to be hardened either by quenching directly from the carburizing temperature or by cooling to room temperature, then reaustenitizing and quenching.
- **carburizing flame**
  - A gas flame that will introduce carbon into some heated metals, as during a gas welding operation. A carburizing flame is a reducing flame, but a reducing flame is not necessarily a carburizing flame.
- **case**

  - In heat treating, that portion of a ferrous alloy, extending inward from the surface, whose composition has been altered during case hardening. Typically considered to be the portion of an alloy (a) whose composition has been measurably altered from the original composition, (b) that appears light when etched, or (c) that has a higher hardness value than the core. Contrast with core .
- **case crushing**
  - A term used to denote longitudinal gouges arising from fracture in case-hardened gears.
- **case hardening**
  - A generic term covering several processes applicable to steel that change the chemical composition of the surface layer by absorption of carbon, nitrogen, or a mixture of the two and, by diffusion, create a concentration gradient. The processes commonly used are carburizing and quench hardening; cyaniding; nitriding; and carbonitriding. The use of the applicable specific process name is preferred.
- **CASS test**
  - Abbreviation for copper-accelerated salt-spray test .
- **castable**
  - In casting, a combination of refractory grain and suitable bonding agent that, after the addition of a proper liquid, is generally poured into place to form a refractory shape or structure that becomes rigid because of chemical action.
- **castability**
  - (1) A complex combination of liquid-metal properties and solidification characteristics that promotes accurate and sound final castings. (2) The relative ease with which a molten metal flows through a mold or casting die.
- **casting**
  - (1) Metal object cast to the required shape by pouring or injecting liquid metal into a mold, as distinct from one shaped by a mechanical process. (2) Pouring molten metal into a mold to produce an object of desired shape.
- **casting defect**
  - Any imperfection in a casting that does not satisfy one or more of the required design or quality specifications. This term is often used in a limited sense for those flaws formed by improper casting solidification.
- **casting shrinkage**
  - The amount of dimensional change per unit length of the casting as it solidifies in the mold or die and cools to room temperature after removal from the mold or die. There are three distinct types of casting shrinkage. Liquid shrinkage refers to the reduction in volume of liquid metal as it cools to the liquidus. Solidification shrinkage is the reduction in volume of metal from the beginning to the end of solidification. Solid shrinkage involves the reduction in volume of metal from the solidus to room temperature.
- **casting strains**
  - Strains in a casting caused by casting stresses that develop as the casting cools.
- **casting stresses**
  - Residual stresses set up when the shape of a casting impedes contraction of the solidified casting during cooling.
- **cast iron**
  - A generic term for a large family of cast ferrous alloys in which the carbon content exceeds the solubility of carbon in austenite at the eutectic temperature. Most cast irons contain at least 2% carbon, plus silicon and sulfur, and may or may not contain other alloying elements. See also compacted graphite iron , ductile iron , gray iron , malleable iron , and white iron .
- **cast steel**
  - Steel in the form of a casting.
- **cast structure**
  - The metallographic structure of a casting evidenced by shape and orientation of grains and by segregation of impurities.
- **catalyst**
  - A substance capable of changing the rate of a reaction without itself undergoing any net change.
- **catastrophic failure**
  - Sudden failure of a component or assembly that frequently results in extensive secondary damage to adjacent components or assemblies.

- **cathode**
  - The negative electrode of an electrolytic cell at which reduction is the principal reaction. (Electrons flow toward the cathode in the external circuit.) Typical cathodic processes are cations taking up electrons and being discharged, oxygen being reduced, and the reduction of an element or group of elements from a higher to a lower valence state. Contrast with anode .
- **cathode copper**
  - Copper deposited at the cathode in electrolytic refining.
- **cathode efficiency**
  - Current efficiency at the cathode.
- **cathode film**
  - The portion of solution in immediate contact with the cathode during electrolysis.
- **cathodic cleaning**
  - Electrolytic cleaning in which the work is the cathode.
- **cathodic corrosion**
  - Corrosion resulting from a cathodic condition of a structure usually caused by the reaction of an amphoteric metal with the alkaline products of electrolysis.
- **cathodic pickling**
  - Electrolytic pickling in which the work is the cathode.
- **cathodic polarization**
  - The change of the electrode potential in the active (negative) direction due to current flow. See also polarization .
- **cathodic protection**
  - (1) Reduction of corrosion rate by shifting the corrosion potential of the electrode toward a less oxidizing potential by applying an external electromotive force. (2) Partial or complete protection of a metal from corrosion by making it a cathode, using either a galvanic or an impressed current. Contrast with anodic protection .
- **cathodic reaction**
  - Electrode reaction equivalent to a transfer of negative charge from the electronic to the ionic conductor. A cathodic reaction is a reduction process. An example common in corrosion is $M(aq)^{2+} + 2e^{-} \rightarrow M(s)$.
- **catholyte**
  - The electrolyte adjacent to the cathode of an electrolytic cell.
- **cation**
  - A positively charged ion that migrates through the electrolyte toward the cathode under the influence of a potential gradient. See also anion and ion .
- **caustic**
  - (1) Burning or corrosive. (2) A hydroxide of a light metal, such as sodium hydroxide or potassium hydroxide.
- **caustic cracking**
  - A form of stress-corrosion cracking most frequently encountered in carbon steels or iron-chromium-nickel alloys that are exposed to concentrated hydroxide solutions at temperatures of 200 to 250 °C (400 to 480 °F). Also known as caustic embrittlement.
- **caustic dip**
  - A strongly alkaline solution into which metal is immersed for etching, for neutralizing acid, or for removing organic materials such as greases or paints.
- **caustic embrittlement**
  - An obsolete historical term denoting a form of stress-corrosion cracking most frequently encountered in carbon steels or iron-chromium-nickel alloys that are exposed to concentrated hydroxide solutions at temperatures of 200 to 250 °C (400 to 480 °F).
- **caustic quenching**
  - Quenching with aqueous solutions of 5 to 10% sodium hydroxide (NaOH).
- **cavitation**
  - The formation and collapse, within a liquid, of cavities or bubbles that contain vapor or gas or both. In general, cavitation originates from a decrease in the static pressure in the liquid. It is distinguished in this way from boiling, which originates from an increase in the liquid temperature. There are certain situations where it may be difficult to make a clear distinction between cavitation and boiling, and the more general definition that is given here is therefore to

be preferred. In order to erode a solid surface by cavitation, it is necessary for the cavitation bubbles to collapse on or close to that surface.

- **cavitation corrosion**
  - A process involving conjoint corrosion and cavitation.
- **cavitation damage**
  - The degradation of a solid body resulting from its exposure to cavitation. This may include loss of material, surface deformation, or changes in properties or appearance.
- **cavitation erosion**
  - Progressive loss of original material from a solid surface due to continuing exposure to cavitation.
- **cavity**
  - The mold or die impression that gives a casting its external shape.
- **CCT diagram**
  - See continuous cooling transformation diagram .
- **cell (electrochemistry)**
  - Electrochemical system consisting of an anode and a cathode immersed in an electrolyte. The anode and cathode may be separate metals or dissimilar areas on the same metal. The cell includes the external circuit, which permits the flow of electrons from the anode toward the cathode. See also electrochemical cell .
- **cementation**
  - The introduction of one or more elements into the outer portion of a metal object by means of diffusion at high temperature.
- **cement copper**
  - Impure copper recovered by chemical deposition when iron (most often shredded steel scrap) is brought into prolonged contact with a dilute copper sulfate solution.
- **cemented carbide**
  - A solid and coherent mass made by pressing and sintering a mixture of powders of one or more metallic carbides, such as tungsten carbide, and a much smaller amount of a metal, such as cobalt, to serve as a binder.
- **cementite**
  - A hard (800 HV), brittle compound of iron and carbon, known chemically as iron carbide and having the approximate chemical formula Fe_3C. It is characterized by an orthorhombic crystal structure. When it occurs as a phase in steel, the chemical composition will be altered by the presence of manganese and other carbide-forming elements. The highest cementite contents are observed in white cast irons, which are used in applications where high wear resistance is required.
- **center drilling**
  - Drilling a short, conical hole in the end of a workpiece--a hole to be used to center the workpiece for turning on a lathe.
- **centerless grinding**
  - Grinding the outside or inside diameter of a cylindrical piece that is supported on a work support blade instead of being held between centers and that is rotated by a so-called regulating or feed wheel.
- **centrifugal casting**
  - The process of filling molds by (1) pouring metal into a sand or permanent mold that is revolving about either its horizontal or its vertical axis or (2) pouring metal into a mold that is subsequently revolved before solidification of the metal is complete. See also centrifuge casting .
- **centrifuge casting**
  - A casting technique in which mold cavities are spaced symmetrically about a vertical axial common downgate. The entire assembly is rotated about that axis during pouring and solidification.
- **ceramic tools**
  - Cutting tools made from sintered, hot-pressed, or hot isostatically pressed alumina-base or silicon nitride-base ceramic materials.
- **cermet**
  - A powder metallurgy product consisting of ceramic particles bonded with a metal.
- **C-frame press**
  - Same as gap-frame press .
- **CG iron**

  - Same as compacted graphite cast iron .
- **chamfer**
  - (1) A beveled surface to eliminate an otherwise sharp corner. (2) A relieved angular cutting edge at a tooth corner.
- **chamfer angle**
  - (1) The angle between a reference surface and the bevel. (2) On a milling contour, the angle between a beveled surface and the axis of the cutter.
- **chamfering**
  - Making a sloping surface on the edge of a member. Also called beveling.
- **chaplet**
  - Metal support that holds a core in place within a casting mold; molten metal solidifies around a chaplet and fuses it into the finished casting.
- **charge**
  - (1) The materials fed into a furnace. (2) Weights of various liquid and solid materials put into a furnace during one feeding cycle.
- **charging**
  - (1) For a lap, impregnating the surface with fine abrasive. (2) Placing materials into a furnace.
- **Charpy test**
  - An impact test in which a V-notched, keyhole-notched, or U-notched specimen, supported at both ends, is struck behind the notch by a striker mounted at the lower end of a bar that can swing as a pendulum. The energy that is absorbed in fracture is calculated from the height to which the striker would have risen had there been no specimen and the height to which it actually rises after fracture of the specimen. Contrast with Izod test .
- **chase (machining)**
  - To make a series of cuts each, except for the first, following in the path of the cut preceding it, as in chasing a thread.
- **chatter**
  - In machining or grinding, (1) a vibration of the tool, wheel, or workpiece producing a wavy surface on the work and (2) the finish produced by such vibration. (3) In tribology, elastic vibrations resulting from frictional or other instability.
- **chatter marks**
  - Surface imperfections on the work being ground, usually caused by vibrations transferred from the wheel-work interface during grinding.
- **check**
  - The intermediate section of a flask that is used between the cope and the drag when molding a shape that requires more than one parting plane.
- **checked edges**
  - Sawtooth edges seen after hot rolling and/or cold rolling.
- **checkers**
  - In a chamber associated with a metallurgical furnace, bricks stacked openly so that heat may be absorbed from the combustion products and later transferred to incoming air when the direction of flow is reversed.
- **checks**
  - (1) Numerous, very fine cracks in a coating or at the surface of a metal part. Checks may appear during processing or during service and are most often associated with thermal treatment or thermal cycling. Also called check marks, or heat checks . (2) Minute cracks in the surface of a casting caused by unequal expansion or contraction during cooling. (3) Cracks in a die impression corner, generally due to forging strains or pressure, localized at some relatively sharp corner. Die blocks too hard for the depth of the die impression have a tendency to check or develop cracks in impression corners. (4) A series of small cracks resulting from thermal fatigue of hot forging dies.
- **chelating agent**
  - (1) An organic compound in which atoms form more than one coordinate bond with metals in solution. (2) A substance used in metal finishing to control or eliminate certain metallic ions present in undesirable quantities.
- **chemical conversion coating**

  - A protective or decorative nonmetallic coating produced in situ by chemical reaction of a metal with a chosen environment. It is often used to prepare the surface prior to the application of an organic coating.
- **chemical deposition**
  - The precipitation or plating-out of a metal from solutions of its salts through the introduction of another metal or reagent to the solution.
- **chemical flux cutting**
  - An oxygen-cutting process in which metals are severed using a chemical flux to facilitate cutting.
- **chemically precipitated powder**
  - A metal powder that is produced as a fine precipitate by chemical displacement.
- **chemical machining**
  - Removing metal stock by controlled selective chemical dissolution.
- **chemical metallurgy**
  - See process metallurgy .
- **chemical milling**
  - The machining process in which metal is formed into intricate shapes by masking certain portions and then etching away the unwanted material.
- **chemical polishing**
  - A process that produces a polished surface by the action of a chemical etching solution. The etching solution is compounded so that peaks in the topography of the surface are dissolved preferentially.
- **chemical vapor deposition (CVD)**
  - A coating process, similar to gas carburizing and carbonitriding, whereby a reactant atmosphere gas is fed into a processing chamber where it decomposes at the surface of the workpiece, liberating one material for either absorption by, or accumulation on, the workpiece. A second material is liberated in gas form and is removed from the processing chamber, along with excess atmosphere gas.
- **chemical wear**
  - See corrosive wear .
- **chevron pattern**
  - A fractographic pattern of radial marks (shear ledges) that look like nested letters "V"; sometimes called a herringbone pattern. Chevron patterns are typically found on brittle fracture surfaces in parts whose widths are considerably greater than their thicknesses. The points of the chevrons can be traced back to the fracture origin.
- **chill**
  - (1) A metal or graphite insert embedded in the surface of a casting sand mold or core or placed in a mold cavity to increase the cooling rate at that point. (2) White iron occurring on a gray or ductile iron casting, such as the chill in the wedge test. See also chilled iron . Compare with inverse chill .
- **chilled iron**
  - Cast iron that is poured into a metal mold or against a mold insert so as to cause the rapid solidification that often tends to produce a white iron structure in the casting.
- **Chinese-script eutectic**
  - A configuration of eutectic constituents, found particularly in some cast alloys of aluminum containing iron and silicon and in magnesium alloys containing silicon, that resembles the characters in Chinese script.
- **chip breaker**
  - (1) Notch or groove in the face of a tool parallel to the cutting edge, designed to break the continuity of the chip. (2) A step formed by an adjustable component clamped to the face of the cutting tool.
- **chipping**
  - (1) Removing seams and other surface imperfections in metals manually with a chisel or gouge, or by a continuous machine, before further processing. (2) Similarly, removing excessive metal.
- **chips**
  - Pieces of material removed from a workpiece by cutting tools or by an abrasive medium.
- **chlorination**

    - (1) Roasting ore in contact with chlorine or a chloride salt to produce chlorides. (2) Removing dissolved gases and entrapped oxides by passing chlorine gas through molten metal such as aluminum and magnesium.
- **chromadizing**
    - Improving paint adhesion on aluminum or aluminum alloys, mainly aircraft skins, by treatment with a solution of chromic acid. Also called chromidizing or chromatizing. Not to be confused with chromating or chromizing .
- **chromate treatment**
    - A treatment of metal in a solution of a hexavalent chromium compound to produce a conversion coating consisting of trivalent and hexavalent chromium compounds.
- **chromating**
    - Performing a chromate treatment.
- **chromizing**
    - A surface treatment at elevated temperature, generally carried out in pack, vapor, or salt baths, in which an alloy is formed by the inward diffusion of chromium into the base metal.
- **chuck**
    - A device for holding work or tools on a machine so that the part can be held or rotated during machining or grinding.
- **CIP**
    - The acronym for cold isostatic pressing .
- **circle grid**
    - A regular pattern of circles, often 2.5 mm (0.1 in.) in diameter, marked on a sheet metal blank.
- **circle-grid analysis**
    - The analysis of deformed circles to determine the severity with which a sheet metal blank has been deformed.
- **circle grinding**
    - Either cylindrical grinding or internal grinding ; the preferred terms.
- **circle shear**
    - A shearing machine with two rotary disk cutters mounted on parallel shafts driven in unison and equipped with an attachment for cutting circles where the desired piece of material is inside the circle. It cannot be employed to cut circles where the desired material is outside the circle.
- **circular field**
    - The magnetic field that (a) surrounds a nonmagnetic conductor of electricity, (b) is completely contained within a magnetic conductor of electricity, or (c) both exists within and surrounds a magnetic conductor. Generally applied to the magnetic field within any magnetic conductor resulting from a current being passed through the part or through a section of the part. Compare with bipolar field .
- **clad brazing sheet**
    - A metal sheet on which one or both sides are clad with brazing filler metal .
- **cladding**
    - (1) A layer of material, usually metallic, that is mechanically or metallurgically bonded to a substrate. Cladding may be bonded to the substrate by any of several processes, such as roll-cladding and explosive forming. (2) A relatively thick layer (1 mm, or 0.04 in.) of material applied by surfacing for the purpose of improved corrosion resistance or other properties. See also coating , surfacing , and hardfacing .
- **clad metal**
    - A composite metal containing two or more layers that have been bonded together. The bonding may have been accomplished by co-rolling, co-extrusion, welding, diffusion bonding, casting, heavy chemical deposition, or heavy electroplating.
- **clamshell marks**
    - Same as beach marks .
- **classification**
    - (1) The separation of ores into fractions according to size and specific gravity, generally in accordance with Stokes' law of sedimentation. (2) Separation of a metal powder into fractions according to particle size.
- **clearance**
    - (1) The gap or space between two mating parts. (2) Space provided between the relief of a cutting tool and the surface that has been cut.

- **cleavage**
  - (1) Fracture of a crystal by crack propagation across a crystallographic plane of low index. (2) The tendency to cleave or split along definite crystallographic planes.
- **cleavage fracture**
  - A fracture, usually of a polycrystalline metal, in which most of the grains have failed by cleavage, resulting in bright reflecting facets. It is one type of crystalline fracture and is associated with low-energy brittle fracture. Contrast with shear fracture .
- **cleavage plane**
  - A characteristic crystallographic plane or set of planes in a crystal on which cleavage fracture occurs easily.
- **climb cutting**
  - Analogous to climb milling .
- **climb milling**
  - Milling in which the cutter moves in the direction of feed at the point of contact.
- **close annealing**
  - Same as box annealing .
- **closed-die forging**
  - The shaping of hot metal completely within the walls or cavities of two dies that come together to enclose the workpiece on all sides. The impression for the forging can be entirely either die or divided between the top and bottom dies. Impression-die forging, often used interchangeably with the term closed-die forging, refers to a closed-die operation in which the dies contain a provision for controlling the flow of excess material, or flash , that is generated. By contrast, in flashless forging, the material is deformed in a cavity that allows little or no escape of excess material.
- **closed dies**
  - Forging or forming impression dies designed to restrict the flow of metal to the cavity within the die set, as opposed to open dies, in which there is little or no restriction to lateral flow.
- **closed pass**
  - A pass of metal through rolls where the bottom roll has a groove deeper than the bar being rolled and the top roll has a collar fitting into the groove, thus producing the desired shape free from flash or fin.
- **close-tolerance forging**
  - A forging held to unusually close dimensional tolerances so that little or no machining is required after forging. See also precision forging .
- **cluster mill**
  - A rolling mill in which each of the two working rolls of small diameter is supported by two or more larger diameter backup rolls.
- **coalescence**
  - (1) The union of particles of a dispersed phase into larger units, usually effected at temperatures below the fusion point. (2) The growing together or growth into one body of the materials being welded. (3) Growth of grains at the expense of the remainder by absorption or the growth of a phase or particle at the expense of the remainder by absorption or reprecipitation.
- **coarsening**
  - An increase in grain size, usually, but not necessarily, by grain growth.
- **coated abrasive**
  - An abrasive product (sandpaper, for example) in which a layer of abrasive particles is firmly attached to a paper, cloth, or fiber backing by means of glue or synthetic-resin adhesive.
- **coated electrode**
  - See preferred terms covered electrode and lightly coated electrode .
- **coating**
  - A relatively thin layer (<1 mm, or 0.04 in.) of material applied by surfacing for the purpose of corrosion prevention, resistance to high-temperature scaling, wear resistance, lubrication, or other purposes.
- **coaxing**
  - Improvement of the fatigue strength of a specimen by the application of a gradually increasing stress amplitude, usually starting below the fatigue limit.
- **coefficient of friction**

  - The dimensionless ratio of the friction force (F) between two bodies to the normal force (N) pressing these bodies together: (μ or f) = (F/N).
- **coercive force**
  - The magnetizing force that must be applied in the direction opposite to that of the previous magnetizing force in order to reduce magnetic flux density to zero; thus, a measure of the magnetic retentivity of magnetic materials.
- **cogging**
  - The reducing operation in working an ingot into a billet with a forging hammer or a forging press.
- **cogging mill**
  - A blooming mill .
- **coherent precipitate**
  - A crystalline precipitate that forms from solid solution with an orientation that maintains continuity between the crystal lattice of the precipitate and the lattice of the matrix, usually accompanied by some strain in both lattices. Because the lattices fit at the interface between precipitate and matrix, there is no discernible phase boundary.
- **cohesion**
  - (1) The state in which the particles of a single substance are held together by primary or secondary valence forces. As used in the adhesive field, the state in which the particles of the adhesive (or adherend) are held together. (2) Force of attraction between the molecules (or atoms) within a single phase. Contrast with adhesion .
- **cohesive strength**
  - (1) The hypothetical stress causing tensile fracture without plastic deformation. (2) The stress corresponding to the forces between atoms.
- **coil**
  - (1) An assembly consisting of one or more magnet wire windings. (2) Rolled metal sheet or strip.
- **coil breaks**
  - Creases or ridges in sheet or strip that appear as parallel lines across the direction of rolling and that generally extend the full width of the sheet or strip.
- **coining**
  - (1) A closed-die squeezing operation, usually performed cold, in which all surfaces of the work are confined or restrained, resulting in a well-defined imprint of the die upon the work. (2) A restriking operation used to sharpen or change an existing radius or profile. (3) The final pressing of a sintered powder metallurgy compact to obtain a definite surface configuration (not to be confused with sizing).
- **coin silver**
  - An alloy containing 90% silver, with copper being the usual alloying element.
- **coke**
  - A porous, gray, infusible product resulting from the dry distillation of bituminous coal, petroleum, or coal tar pitch that drives off most of the volatile matter. Used as a fuel in cupola melting.
- **cold box process**
  - In foundry practice, a two-part organic resin binder system mixed in conventional mixers and blown into shell or solid core shapes at room temperature. A vapor mixed with air is blown into the core, permitting instant setting and immediate pouring of metal around it.
- **cold chamber machine**
  - A die casting machine with an injection system that is charged with liquid metal from a separate furnace. Compare with hot chamber machine .
- **cold compacting**
  - See preferred term cold pressing .
- **cold cracking**
  - (1) Cracks in cold or nearly cold cast metal due to excessive internal stress caused by contraction. Often brought about when the mold is too hard or the casting is of unsuitable design. (2) A type of weld cracking that usually occurs below 205 °C (400 °F). Cracking may occur during or after cooling to room temperature, sometimes with a considerable time delay. Three factors combine to produce cold cracks; stress (for example, from thermal expansion and contraction), hydrogen (from hydrogen-containing welding consumables), and a susceptible microstructure (plate martensite is most susceptible to cracking, ferritic and bainitic structures are least susceptible). See also hot cracking , lamellar tearing , and stress-relief cracking .

- **cold die quenching**
  - A quench utilizing cold, flat, or shaped dies to extract heat from a part. Cold die quenching is slow, expensive, and is limited to smaller parts with large surface areas.
- **cold heading**
  - Working metal at room temperature such that the cross-sectional area of a portion or all of the stock is increased. See also heading and upsetting .
- **cold inspection**
  - A visual (usually final) inspection of forgings for visible imperfections, dimensions, weight, and surface condition at room temperature. The term may also be used to describe certain nondestructive tests such as magnetic-particle, dye-penetrant, and sonic inspection.
- **cold isostatic pressing (CIP)**
  - Forming technique in which high fluid pressure is applied to a powder (metal or ceramic) part at ambient temperature. Water or oil is used as the pressure medium.
- **cold lap**
  - (1) Wrinkled markings on the surface of an ingot or casting from incipient freezing of the surface and too low a casting temperature. (2) A flaw that results when a workpiece fails to fill the die cavity during the first forging. A seam is formed as subsequent dies force metal over this gap to leave a seam on the workpiece surface. See also cold shut .
- **cold mill**
  - A mill for cold rolling of sheet or strip.
- **cold pressing**
  - Forming a powder metallurgy compact at a temperature low enough to avoid sintering, usually room temperature. Contrast with hot pressing .
- **cold-rolled sheets**
  - A metal mill product produced from a hot-rolled pickled coil that has been given substantial cold reduction at room temperature. The resulting product usually requires further processing to make it suitable for most common applications. The usual end product is characterized by improved surface, greater uniformity in thickness, and improved mechanical properties compared with hot-rolled sheet.
- **cold-setting process**
  - In foundry practice, any of several systems for bonding mold or core aggregates by means of organic binders, relying on the use of catalysts rather than heat for polymerization (setting).
- **cold shortness**
  - Brittleness that exists in some metals at temperatures below the recrystallization temperature.
- **cold shot**
  - (1) A portion of the surface of an ingot or casting showing premature solidification; caused by splashing of molten metal onto a cold mold wall during pouring. (2) Small globule of metal embedded in, but not entirely fused with, the casting.
- **cold shut**
  - (1) A discontinuity that appears on the surface of cast metal as a result of two streams of liquid meeting and failing to unite. (2) A lap on the surface of a forging or billet that was closed without fusion during deformation. (3) Freezing of the top surface of an ingot before the mold is full.
- **Coldstream process**
  - In powder metallurgy, a method of producing cleavage fractures in hard particles through particle impingements in a high-velocity cold gas stream. Also referred to as impact crushing.
- **cold treatment**
  - Exposing steel to suitable subzero temperatures (-85 °C, or -120 °F) for the purpose of obtaining desired conditions or properties such as dimensional or microstructural stability. When the treatment involves the transformation of retained austenite, it is usually followed by tempering.
- **cold trimming**
  - The removal of flash or excess metal from a forging at room temperature in a trimming press.
- **cold welding**
  - A solid-state welding process in which pressure is used at room temperature to produce coalescence of metals with substantial deformation at the weld. Compare with hot pressure welding , diffusion welding , and forge welding .
- **cold work**
  - Permanent strain in a metal accompanied by strain hardening.
- **cold-worked structure**

    - A microstructure resulting from plastic deformation of a metal or alloy below its recrystallization temperature.
- **cold working**
    - Deforming metal plastically under conditions of temperature and strain rate that induce strain hardening. Usually, but not necessarily, conducted at room temperature. Contrast with hot working .
- **collapsibility**
    - The tendency of a sand mixture to break down under the pressures and temperatures developed during casting.
- **collet**
    - A split sleeve used to hold work or tools during machining or grinding.
- **color buffing**
    - Producing a final high luster by buffing. Sometimes called coloring .
- **coloring**
    - Producing desired colors on metal by a chemical or electrochemical reaction. See also color buffing .
- **columnar structure**
    - A coarse structure of parallel elongated grains formed by unidirectional growth, most often observed in castings, but sometimes seen in structures resulting from diffusional growth accompanied by a solid-state transformation.
- **combination die**
    - (1) A die-casting die having two or more different cavities for different castings. (2) For forming, see compound die .
- **combination mill**
    - An arrangement of a continuous mill for roughing and a guide mill or looping mill for shaping.
- **combined carbon**
    - Carbon in iron or steel that is combined chemically with other elements; not in the free state as graphite or temper carbon. The difference between the total carbon and the graphite carbon analyses. Contrast with free carbon .
- **combined cyanide**
    - The cyanide of a metal-cyanide complex ion.
- **combined stresses**
    - Any state of stress that cannot be represented by a single component of stress; that is, one that is more complicated than simple tension, compression, or shear.
- **combustion analysis**
    - An analytical technique for determining the concentration of carbon and sulfur in samples. The sample is burned in a graphite crucible in the presence of oxygen, which causes carbon and sulfur to leave the sample as carbon dioxide and sulfur dioxide. These gases are then detected by infrared or thermal conductive means.
- **comet tails**
    - A group of comparatively deep unidirectional scratches that form adjacent to a microstructural discontinuity during mechanical polishing. They have the general shape of a comet tail. Comet tails form only when a unidirectional motion is maintained between the surface being polished and the polishing cloth.
- **comminution**
    - (1) Breaking up or grinding an ore into small fragments. (2) Reducing metal to powder by mechanical means. (3) The act or process of reduction of powder particle size, usually but not necessarily by grinding or milling. See also pulverization .
- **compact**
    - (1) The object produced by the compression of metal powder, generally while confined in a die. (2) The operation or process of producing a compact; sometimes called pressing.
- **compacted graphite iron**
    - Cast iron having a graphite shape intermediate between the flake form typical of gray cast iron and the spherical form of fully spherulitic ductile cast iron. An acceptable compacted graphite iron structure is one that contains no flake graphite, <20% spheroidal graphite, and 80% compacted graphite (ASTM A 247, type IV). Also known as CG iron or vermicular iron, compacted graphite cast iron is produced in a manner similar to that for ductile cast iron, but using a technique that inhibits the formation of fully spherulitic graphite nodules.

- **compacting pressure**
  - In powder metallurgy, the specific compacting force related to the area of contact with the press punch expressed in megapascals, meganewtons per square meter, or tons per square inch.
- **compaction**
  - (1) The act of forcing particulate or granular material together (consolidation) under pressure or impact to yield a relatively dense mass or formed object. (2) In powder metallurgy, the preparation of a compact or object produced by the compression of a powder, generally while confined in a die, with or without the inclusion of lubricants, binders, and so forth. With or without the concurrent applications of heat.
- **compatibility**
  - A measure of the extent to which materials are mutually soluble in the solid state.
- **complete fusion**
  - Fusion that has occurred over the entire base material surfaces intended for welding and between all layers and weld beads.
- **complexing agent**
  - A substance that is an electron donor and that will combine with a metal ion to form a soluble complex ion.
- **complexion**
  - An ion that may be formed by the addition reaction of two or more other ions.
- **component**
  - (1) One of the elements or compounds used to define a chemical (or alloy) system, including all phases, in terms of the fewest substances possible. (2) One of the individual parts of a vector as referred to a system of coordinates. (3) An individual functional element in a physically independent body that cannot be further reduced or divided without destroying its stated function, for example, a resistor, capacitor, diode, or transistor.
- **composite coating**
  - A coating on a metal or nonmetal that consists of two or more components, one of which is often particulate in form. Example: a cermet composite coating on a cemented carbide cutting tool. Also known as multilayer coating.
- **composite electrode**
  - A welding electrode made from two or more distinct components, at least one of which is filler metal. A composite electrode may exist in any of various physical forms, such as stranded wires, filled tubes, or covered wire.
- **composite joint**
  - A joint in which welding is used in conjunction with mechanical joining.
- **composite material**
  - A combination of two or more materials (reinforcing elements, fillers, and composite matrix binder), differing in form or composition on a macroscale. The constituents retain their identities, that is, they do not dissolve or merge completely into one another although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another. Examples are cermets and metal-matrix composites.
- **composite plate**
  - An electrodeposit consisting of layers of at least two different compositions.
- **composite powder**
  - A powder in which each particle consists of two or more different materials.
- **composite structure**
  - A structural member (such as a panel, plate, pipe, or other shape) that is built up by bonding together two or more distinct components, each of which may be made of a metal, alloy, nonmetal, or composite material. Examples of composite structures include: honeycomb panels, clad plate, electrical contacts, sleeve bearings, carbide-tipped drills or lathe tools, and weldments constructed of two or more different alloys.
- **compound compact**
  - A powder metallurgy compact consisting of mixed metals, the particles of which are joined by pressing or sintering, or both, with each metal particle retaining substantially its original composition.
- **compound die**

    - Any die designed to perform more than one operation on a part with one stroke of the press, such as blanking and piercing, in which all functions are performed simultaneously within the confines of the blank size being worked.
- **compressibility**
    - (1) The ability of a powder to be formed into a compact having well-defined contours and structural stability at a given temperature and pressure; a measure of the plasticity of powder particles. (2) A density ratio determined under definite testing conditions. Also referred to as compactibility.
- **compression ratio (powder metallurgy)**
    - The ratio of the volume of the loose powder to the volume of the compact made from it.
- **compressive strength**
    - The maximum compressive stress that a material is capable of developing, based on original area of cross section. If a material fails in compression by a shattering fracture, the compressive strength has a very definite value. If a material does not fail in compression by a shattering fracture, the value obtained for compressive strength is an arbitrary value depending on the degree of distortion that is regarded as indicating complete failure of the material.
- **compressive stress**
    - A stress that causes an elastic body to deform (shorten) in the direction of the applied load. Contrast with tensile stress .
- **concentration**
    - (1) The mass of a substance contained in a unit volume of sample, for example, grams per liter. (2) A process for enrichment of an ore in valuable mineral content by separation and removal of waste material, or gangue.
- **concentration cell**
    - An electrolytic cell, the electromotive force of which is caused by a difference in concentration of some component in the electrolyte. This difference leads to the formation of discrete cathode and anode regions.
- **concentration polarization**
    - That portion of the polarization of a cell produced by concentration changes resulting from passage of current through the electrolyte.
- **concurrent heating**
    - The application of supplemental heat to a structure during a welding or cutting operation.
- **conditioning heat treatment**
    - A preliminary heat treatment used to prepare a material for a desired reaction to a subsequent heat treatment. For the term to be meaningful, the exact heat treatment must be specified.
- **cone**
    - The conical part of an oxyfuel gas flame next to the orifice of the tip.
- **cone angle**
    - The angle that the cutter axis makes with the direction along which the blades are moved for adjustment, as in adjustable-blade reamers where the base of the blade slides on a conical surface.
- **conformal coating**
    - A coating that covers and exactly fits the shape of the coated object.
- **congruent melting**
    - An isothermal or isobaric melting in which both the solid and liquid phases have the same composition throughout the transformation.
- **congruent transformation**
    - An isothermal or isobaric phase change in metals in which both of the phases concerned have the same composition throughout the process.
- **conjugate phases**
    - In microstructural analysis, those states of matter of unique composition that coexist at equilibrium at a single point in temperature and pressure. For example, the two coexisting phases of a two-phase equilibrium.
- **constant life fatigue diagram**
    - In failure analysis, a plot (usually on rectangular coordinates) of a family of curves, each of which is for a single fatigue life (number of cycles), relating alternating stress, maximum stress, minimum stress, and mean stress. The constant life fatigue diagram is generally derived from a family of *S*-*N* curves, each of which represents a different stress ratio for a 50% probability of

survival. See also nominal stress , maximum stress , minimum stress , *S-N* curve , fatigue life , and stress ratio .

- **constituent**
  - (1) One of the ingredients that make up a chemical system. (2) A phase or a combination of phases that occurs in a characteristic configuration in an alloy microstructure.
- **constitution diagram**
  - See phase diagram .
- **constraint**
  - Any restriction that limits the transverse contraction normally associated with a longitudinal tension and that hence causes a secondary tension in the transverse direction; usually used in connection with welding. Contrast with restraint .
- **consumable electrode**
  - A general term for any arc welding electrode made chiefly of filler metal. Use of specific names such as covered electrode , bare electrode , flux cored electrode , and lightly coated electrode is preferred.
- **consumable-electrode remelting**
  - A process for refining metals in which an electric current passes between an electrode made of the metal to be refined and an ingot of the refined metal, which is contained in a water-cooled mold. As a result of the passage of electric current, droplets of molten metal form on the electrode and fall to the ingot. The refining action occurs from contact with the atmosphere, vacuum, or slag through which the drop falls. See also electroslag remelting and vacuum arc remelting .
- **contact corrosion**
  - A term primarily used in Europe to describe galvanic corrosion between dissimilar metals.
- **contact fatigue**
  - Cracking and subsequent pitting of a surface subjected to alternating Hertzian stresses such as those produced under rolling contact or combined rolling and sliding. The phenomenon of contact fatigue is encountered most often in rolling-element bearings or in gears, where the surface stresses are high due to the concentrated loads and are repeated many times during normal operation.
- **contact plating**
  - A metal plating process wherein the plating current is provided by galvanic action between the work metal and a second metal, without the use of an external source of current.
- **contact potential**
  - In corrosion technology, the potential difference at the junction of two dissimilar substances.
- **container**
  - The chamber into which an ingot or billet is inserted prior to extrusion. The container for backward extrusion of cups or cans is sometimes called a die.
- **contaminant**
  - An impurity or foreign substance present in a material or environment that affects one or more properties of the material.
- **continuous casting**
  - A casting technique in which a cast shape is continuously withdrawn through the bottom of the mold as it solidifies, so that its length is not determined by mold dimensions. Used chiefly to produce semifinished mill products such as billets, blooms, ingots, slabs, strip, and tubes. See also strand casting .
- **continuous cooling transformation (CCT) diagram**
  - Set of curves drawn using logarithmic time and linear temperature as coordinates, which define, for each cooling curve of an alloy, the beginning and end of the transformation of the initial phase.
- **continuous mill**
  - A rolling mill consisting of a number of strands of synchronized rolls (in tandem) in which metal undergoes successive reductions as it passes through the various strands.
- **continuous phase**
  - In an alloy or portion of an alloy containing more than one phase, the phase that forms the matrix in which the other phase or phases are dispersed.
- **continuous precipitation**

    - Precipitation from a supersaturated solid solution in which the precipitate particles grow by long-range diffusion without recrystallization of the matrix. Continuous precipitates grow from nuclei distributed more or less uniformly throughout the matrix. They usually are randomly oriented, but may form a Widmanstätten structure. Also called general precipitation. Compare with discontinuous precipitation and localized precipitation .
- **continuous-type furnace**
    - A furnace used for heat treating materials that progress continuously through the furnace, entering one door and being discharged from another.
- **continuous weld**
    - A weld extending continuously from one end of a joint to the other or, where the joint is essentially circular, completely around the joint. Contrast with intermittent weld .
- **contour forming**
    - See roll forming , stretch forming , tangent bending , and wiper forming .
- **contour machining**
    - Machining of irregular surfaces, such as those generated in tracer turning, tracer boring, and tracer milling.
- **contour milling**
    - Milling of irregular surfaces. See also tracer milling .
- **contraction**
    - The volume change that occurs in metals and alloys upon solidification and cooling to room temperature.
- **controlled atmosphere**
    - (1) A specified inert gas or mixture of gases at a predetermined temperature in which selected processes take place. (2) As applied to sintering, to prevent oxidation and destruction of the powder compacts.
- **controlled cooling**
    - Cooling a metal or alloy from an elevated temperature in a predetermined manner to avoid hardening, cracking, or internal damage, or to produce desired microstructure or mechanical properties.
- **controlled-pressure cycle**
    - A forming cycle during which the hydraulic pressure in the forming cavity is controlled by an adjustable cam that is coordinated with the punch travel.
- **controlled rolling**
    - A hot-rolling process in which the temperature of the steel is closely controlled, particularly during the final rolling passes, to produce a fine-grain microstructure.
- **conventional forging**
    - A forging characteristic by design complexity and tolerances that falls within the broad range of general forging practice.
- **conventional milling**
    - Milling in which the cutter moves in the direction opposite to the feed at the point of contact. Contrast with climb milling .
- **conventional strain**
    - See engineering strain and strain .
- **conventional stress**
    - See engineering stress and stress .
- **conversion coating**
    - A coating consisting of a compound of the surface metal, produced by chemical or electrochemical treatments of the metal. Examples include chromate coatings on zinc, cadmium, magnesium, and aluminum, and oxide and phosphate coatings on steel. See also chromate treatment and phosphating .
- **converter**
    - A furnace in which air is blown through a bath of molten metal or matte, oxidizing the impurities and maintaining the temperature through the heat produced by the oxidation reaction. A typical converter is the argon oxygen decarburization vessel.
- **coolant**
    - The liquid used to cool the work during grinding and to prevent it from rusting. It also lubricates, washes away chips and grits, and aids in obtaining a finer finish. In metal cutting, the preferred term is cutting fluid.

- **cooling curve**
  - A graph showing the relationship between time and temperature during the cooling of a material. It is used to find the temperatures at which phase changes occur. A property or function other than time may occasionally be used--for example, thermal expansion.
- **cooling rate**
  - The average slope of the time-temperature curve taken over a specified time and temperature interval.
- **cooling stresses**
  - Residual stresses in castings resulting from nonuniform distribution of temperature during cooling.
- **cope**
  - In casting, the upper or topmost section of a flask, mold, or pattern.
- **copper-accelerated salt-spray (CASS) test**
  - An accelerated corrosion test for some electrodeposits and for anodic coatings on aluminum.
- **copper brazing**
  - A term improperly used to denote brazing with a copper filler metal.
- **core**
  - (1) A specially formed material inserted in a mold to shape the interior or other part of a casting that cannot be shaped as easily by the pattern. (2) In a ferrous alloy prepared for case hardening, that portion of the alloy that is not part of the case. Typically considered to be the portion that (a) appears dark (with certain etchants) on an etched cross section, (b) has an essentially unaltered chemical composition, or (c) has a hardness, after hardening, less than a specified value.
- **core assembly**
  - In casting, a complex core consisting of a number of sections.
- **core binder**
  - In casting, any material used to hold the grains of core sand together.
- **core blow**
  - A gas pocket in a casting adjacent to a cored cavity and caused by entrapped gases from the core.
- **core blower**
  - A machine for making foundry cores using compressed air to blow and pack the sand into the core box.
- **core box**
  - In casting, a wood, metal, or plastic structure containing a shaped cavity into which sand is packed to make a core.
- **cored bars**
  - In powder metallurgy, a compact of bar shape heated by its own electrical resistance to a temperature high enough to melt its interior.
- **core forging**
  - (1) Displacing metal with a punch to fill a die cavity. (2) The product of such an operation.
- **core knockout machine**
  - In casting, a mechanical device for removing cores from castings.
- **core rod**
  - In powder metallurgy, a member of a die assembly used in molding a hole in a compact.
- **core sand**
  - In casting, sand for making cores to which a binding material has been added to obtain good cohesion and permeability after drying; usually low in clays.
- **coring**
  - (1) A condition of variable composition between the center and surface of a unit of microstructure (such as a dendrite, grain, carbide particle); results from nonequilibrium solidification, which occurs over a range of temperature. (2) A central cavity at the butt end of a rod extrusion, sometimes called extrusion pipe .
- **corona (resistance welding)**
  - The area sometimes surrounding the nugget of a spot weld at the faying surfaces which provides a degree of solid-state welding.
- **corrodkote test**
  - An accelerated corrosion test for electrodeposits.
- **corrosion**

  - The chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties.
- **corrosion effect**
  - A change in any part of the corrosion system caused by corrosion.
- **corrosion embrittlement**
  - The severe loss of ductility of a metal resulting from corrosive attack, usually intergranular and often not visually apparent.
- **corrosion-erosion**
  - See erosion-corrosion .
- **corrosion fatigue**
  - The process in which a metal fractures prematurely under conditions of simultaneous corrosion and repeated cyclic loading at lower stress levels or fewer cycles than would be required in the absence of the corrosive environment.
- **corrosion inhibitor**
  - See inhibitor .
- **corrosion potential (E_{corr})**
  - The potential of a corroding surface in an electrolyte, relative to a reference electrode. Also called rest potential, open-circuit potential, or freely corroding potential.
- **corrosion product**
  - Substance formed as a result of corrosion.
- **corrosion protection**
  - Modification of a corrosion system so that corrosion damage is mitigated.
- **corrosion rate**
  - Corrosion effect on a metal per unit of time. The type of corrosion rate used depends on the technical system and on the type of corrosion effect. Thus, corrosion rate may be expressed as an increase in corrosion depth per unit of time (penetration rate, for example, mils/yr) or the mass of metal turned into corrosion products per unit area of surface per unit of time (weight loss, for example, $g/m^2/yr$). The corrosion effect may vary with time and may not be the same at all points of the corroding surface. Therefore, reports of corrosion rates should be accompanied by information on the type, time dependency, and location of the corrosion effect.
- **corrosion resistance**
  - The ability of a material to withstand contact with ambient natural factors or those of a particular, artificially created atmosphere, without degradation or change in properties. For metals, this could be pitting or rusting; for organic materials, it could be crazing.
- **corrosion system**
  - System consisting of one or more metals and all parts of the environment that influence corrosion.
- **corrosive wear**
  - Wear in which chemical or electrochemical reaction with the environment is significant. See also oxidative wear .
- **corrugating**
  - The forming of sheet metal into a series of straight, parallel alternate ridges and grooves with a rolling mill equipped with matched roller dies or a press brake equipped with a specially shaped punch and die.
- **corrugations**
  - In metalforming, transverse ripples caused by a variation in strip shape during hot or cold reduction.
- **Cottrell process**
  - Removal of solid particulates from gases with electrostatic precipitation.
- **coulometer**
  - An electrolytic cell arranged to measure the quantity of electricity by the chemical action produced in accordance with Faraday's law.
- **counterblow hammer**
  - A forging hammer in which both the ram and the anvil are driven simultaneously toward each other by air or steam pistons.
- **counterboring**
  - Removal of material to enlarge a hole for part of its depth with a rotary, pilot guided, end cutting tool having two or more cutting lips and usually having straight or helical flutes for the passage of chips and the admission of a cutting fluid.

- **countersinking**
  - Beveling or tapering the work material around the periphery of a hole creating a concentric surface at an angle less than 90° with the centerline of the hole for the purpose of chamfering holes or recessing screw and rivet heads.
- **covered electrode**
  - A composite filler metal electrode consisting of a core of a bare electrode or metal cored electrode to which a covering sufficient to provide a slag layer on the weld metal has been applied. The covering may contain materials providing such functions as shielding from the atmosphere, deoxidation, and arc stabilization and can serve as a source of metallic additions to the weld. Compare with lightly coated electrode .
- **covering power**
  - (1) The ability of a solution to give satisfactory plating at very low current densities, a condition that exists in recesses and pits. This term suggests an ability to cover, but not necessarily to build up, a uniform coating, whereas throwing power suggests the ability to obtain a coating of uniform thickness on an irregularly shaped object. (2) The degree to which a porcelain enamel coating obscures the underlying surface.
- **crack**
  - (1) A fracture type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement. (2) A line of fracture without complete separation.
- **crack growth**
  - Rate of propagation of a crack through a material due to a static or dynamic applied load.
- **crack length (depth) (*a*)**
  - In fatigue and stress-corrosion cracking, the physical crack size used to determine the crack growth rate and the stress-intensity factor. For a compact-type specimen, crack length is measured from the line connecting the bearing points of load application. For a center-crack tension specimen, crack length is measured from the perpendicular bisector of the central crack. See also crack size .
- **crack mouth opening displacement (CMOD)**
  - See crack opening displacement .
- **crack opening displacement**
  - On a K_{Ic} specimen, the opening displacement of the notch surfaces at the notch and in the direction perpendicular to the plane of the notch and the crack. The displacement at the tip is called the crack tip opening displacement (CTOD); at the mouth, it is called the crack mouth opening displacement (CMOD). See also stress-intensity factor for definition of K_{Ic}.
- **crack size (*a*)**
  - A lineal measure of a principal planar dimension of a crack. This measure is commonly used in the calculation of quantities descriptive of the stress and displacement fields. In practice, the value of crack size is obtained from procedures for measurement of physical crack size, original crack size, or effective crack size, as appropriate to the situation under consideration. See also crack length (depth) .
- **crack tip opening displacement (CTOD)**
  - See crack opening displacement .
- **crank press**
  - A mechanical press whose slides are actuated by a crankshaft.
- **crater**
  - In arc welding, a depression at the termination of a weld bead or in the molten weld pool.
- **crater crack**
  - A crack in the crater of a weld bead.
- **crater wear**
  - The wear that occurs on the rake face of a cutting tool due to contact with the material in the chip that is sliding along that face.
- **craze cracking**
  - Irregular surface cracking of a metal associated with thermal cycling. This term is used more in the United Kingdom than in the United States, where the term checking is used instead. See also checks .
- **creep**

    - Time-dependent strain occurring under stress. The creep strain occurring at a diminishing rate is called primary creep; that occurring at a minimum and almost constant rate, secondary creep; and that occurring at an accelerating rate, tertiary creep.
- **creep-feed grinding**
    - A grinding process that produces deeper cuts at slow traverse rates.
- **creep limit**
    - (1) The maximum stress that will cause less than a specified quantity of creep in a given time. (2) The maximum nominal stress under which the creep strain rate decreases continuously with time under constant load and at constant temperature. Sometimes used synonymously with creep strength.
- **creep rate**
    - The slope of the creep-time curve at a given time. Deflection with time under a given static load.
- **creep recovery**
    - The time-dependent decrease in strain in a solid, following the removal of force.
- **creep-rupture embrittlement**
    - Embrittlement under creep conditions. Failure occurs by intergranular cracking of the embrittled material.
- **creep-rupture strength**
    - The stress that causes fracture in a creep test at a given time, in a specified constant environment. This is sometimes referred to as the stress-rupture strength.
- **creep-rupture test**
    - A test in which progressive specimen deformation and the time for rupture are both measured. In general, deformation is much greater than that developed during a creep test. Also known as stress-rupture test.
- **creep strain**
    - The time-dependent total strain (extension plus initial gage length) produced by applied stress during a creep test.
- **creep strength**
    - The stress that will cause a given creep strain in a creep test at a given time in a specified constant environment.
- **creep stress**
    - The constant load divided by the original cross-sectional area of the specimen.
- **creep test**
    - A method of determining the extension of metals under a given load at a given temperature. The determination usually involves the plotting of time-elongation curves under constant load; a single test may extend over many months. The results are often expressed as the elongation (in millimeters or inches) per hour on a given gage length (e.g., 25 mm, or 1 in.).
- **crevice corrosion**
    - Localized corrosion of a metal surface at, or immediately adjacent to, an area that is shielded from full exposure to the environment because of close proximity between the metal and the surface of another material.
- **crimping**
    - The forming of relatively small corrugations in order to set down and lock a seam, to create an arc in a strip of metal, or to reduce an existing arc or diameter. See also corrugating .
- **critical cooling rate**
    - The minimum rate of continuous cooling for preventing undesirable transformations. For steel, unless otherwise specified, it is the slowest rate at which austenite can be cooled from above critical temperature to prevent its transformation above the martensite start temperature.
- **critical current density**
    - In an electrolytic process, a current density at which an abrupt change occurs in an operating variable or in the nature of an electrodeposit or electrode film.
- **critical flaw size**
    - The size of a flaw (defect) in a structure that will cause failure at a particular stress level.
- **critical point**
    - (1) The temperature or pressure at which a change in crystal structure, phase, or physical properties occurs. Also termed transformation temperature . (2) In an equilibrium diagram, that combination of composition, temperature, and pressure at which the phases of an inhomogeneous system are in equilibrium.

- **critical shear stress**
    - The shear stress required to cause slip in a designated slip direction on a given slip plane. It is called the critical resolved shear stress if the shear stress is induced by tensile or compressive forces acting on the crystal.
- **critical strain**
    - (1) In mechanical testing, the strain at the yield point. (2) The strain just sufficient to cause recrystallization; because the strain is small, usually only a few percent, recrystallization takes place from only a few nuclei, which produces a recrystallized structure consisting of very large grains.
- **critical stress-intensity factor**
    - See stress-intensity factor .
- **critical temperature**
    - That temperature above which the vapor phase cannot be condensed to liquid by an increase in pressure. Synonymous with critical point if pressure is constant.
- **critical temperature range**
    - Synonymous with transformation ranges , which is the preferred term.
- **Croning process**
    - In casting, a shell molding process that uses a phenolic resin binder. Sometimes referred to as C process or Chronizing.
- **crop**
    - (1) An end portion of an ingot that is cut off as scrap. (2) To shear a bar or billet.
- **cross breaks**
    - Same as coil breaks .
- **cross-country mill**
    - A rolling mill in which the mill stands are so arranged that their tables are parallel with a transfer (or crossover) table connecting them. Such a mill is used for rolling structural shapes, rails, and any special form of bar stock not rolled in the ordinary bar mill.
- **cross direction**
    - See transverse direction .
- **cross forging**
    - Preliminary working of forging stock in flat dies to develop mechanical properties, particularly in the center portions of heavy sections.
- **cross rolling**
    - Rolling of metal or sheet or plate so that the direction of rolling is about 90° from the direction of a previous rolling.
- **cross-wire weld**
    - A weld made at the junction between crossed wires or bars.
- **crown**
    - (1) The upper part (head) of a forming press frame. On hydraulic presses, the crown usually contains the cylinder; on mechanical presses, the crown contains the drive mechanism. See also hydraulic press and mechanical press . (2) A shape (crown) ground into a flat roll to ensure flatness of cold- (and hot-) rolled sheet and strip. (3) A contour on a sheet or roll where the thickness or diameter increases from edge to center.
- **crucible furnace**
    - A melting or holding furnace in which the molten metal is contained in a pot-shaped (hemispherical) shell. Electric heaters or fuel-fired burners outside the shell generate the heat that passes through the shell (crucible) to the molten metal.
- **crush**
    - (1) Buckling or breaking of a section of a casting mold due to incorrect register when the mold is closed. (2) An indentation in the surface of a casting due to displacement of sand when the mold was closed.
- **crush forming**
    - Shaping a grinding wheel by forcing a rotating metal roll into its face so as to reproduce the desired contour.
- **crushings test**
    - (1) A radial compressive test applied to tubing, sintered-metal bearings, or other similar products for determining radial crushing strength (maximum load in compression). (2) An axial compressive test for determining quality of tubing, such as soundness of weld in welded tubing.

- **cryogenic treatment**
    - See cold treatment .
- **crystal**
    - (1) A solid composed of atoms, ions, or molecules arranged in a pattern that is repetitive in three dimensions. (2) That form, or particle, or piece of a substance in which its atoms are distributed in one specific orderly geometrical array, called a "lattice," essentially throughout. Crystals exhibit characteristic optical and other properties and growth or cleavage surfaces, in characteristic directions.
- **crystalline**
    - That form of a substance that comprises predominantly (one or more) crystals, as opposed to glassy or amorphous.
- **crystalline fracture**
    - A pattern of brightly reflecting crystal facets on the fracture surface of a polycrystalline metal, resulting from cleavage fracture of many individual crystals. Contrast with fibrous fracture , and silky fracture ; see also granular fracture .
- **crystallization**
    - (1) The separation, usually from a liquid phase on cooling, of a solid crystalline phase. (2) The progressive process in which crystals are first nucleated (started) and then grown in size within a host medium that supplies their atoms. The host may be gas, liquid, or of another crystalline form.
- **crystal orientation**
    - See orientation .
- **crystal system**
    - One of seven groups into which all crystals may be divided; triclinic, monoclinic, orthorhombic, hexagonal, rhombohedral, tetragonal, and cubic.
- **cubic plane**
    - A plane perpendicular to any one of the three crystallographic axes of the cubic (isometric) system; the Miller indices are {100}.
- **cup**
    - (1) A sheet metal part; the product of the first drawing operation. (2) Any cylindrical part or shell closed at one end.
- **cup-and-cone-fracture**
    - A mixed-mode fracture, often seen in tensile-test specimens of a ductile material, where the central portion undergoes plane-strain fracture and the surrounding region undergoes plane-stress fracture. It is called a cup fracture (or cup-and-cone fracture) because one of the mating fracture surfaces looks like a miniature cup--that is, it has a central depressed flat-face region surrounded by a shear lip; the other fracture surface looks like a miniature truncated cone.
- **cupellation**
    - Oxidation of molten lead containing gold and silver to produce lead oxide, thereby separating the precious metals from the base metal.
- **cupola**
    - A cylindrical vertical furnace for melting metal, especially cast iron, by having the charge come in contact with the hot fuel, usually metallurgical coke.
- **cupping**
    - (1) The first step in deep drawing. (2) Fracture of severely worked rods or wire where one end has the appearance of a cup and the other that of a cone.
- **cupping test**
    - A mechanical test used to determine the ductility and stretching properties of sheet metal. It consists of measuring the maximum part depth that can be formed before fracture. The test is typically carried out by stretching the test piece clamped at its edges into a circular die using a punch with a hemispherical end. See also Erichsen test , Olsen ductility test , and Swift cup test .
- **Curie temperature**
    - The temperature marking the transition between ferromagnetism and paramagnetism, or between the ferroelectric phase and the paraelectric phase. Also known as Curie point. See also ferromagnetism and paramagnetism .
- **curling**
    - Rounding the edge of sheet metal into a closed or partly closed loop.
- **current**

  - The net transfer of electric charge per unit time. Also called electric current. See also current density .
- **current decay**
  - In spot, seam, or projection welding, the controlled reduction of the welding current from its peak amplitude to a lower value to prevent excessively rapid cooling of the weld nugget.
- **current density**
  - The current flowing to or from a unit area of an electrode surface.
- **current efficiency**
  - (1) The ratio of the electrochemical equivalent current density for a specific reaction to the total applied current density. (2) The proportion of current used in a given process to accomplish a desired result; in electroplating, the proportion used in depositing or dissolving metal.
- **cut (foundry practice)**
  - (1) To recondition molding sand by mixing on the floor with a shovel or blade-type machine. (2) To form the sprue cavity in a mold. (3) Defect in a casting resulting from erosion of the sand by metal flowing over the mold or cored surface.
- **cut edge**
  - A mechanically sheared edge obtained by slitting, shearing, or blanking.
- **cut-off (casting)**
  - Removing a casting from the sprue by refractory wheel or saw, arc-air torch, or gas torch.
- **cut-off (metalforming)**
  - A pair of blades positioned in dies or equipment (or a section of the die milled to produce the same effect as inserted blades) used to separate the forging from the bar after forging operations are completed. Used only when forgings are produced from relatively long bars instead of from individual, precut multiples or blanks. See also blank and multiple .
- **cutoff wheel**
  - A thin abrasive wheel for severing or slotting any material or part.
- **cutting down**
  - Removing roughness or irregularities of a metal surface by abrasive action.
- **cutting edge**
  - The leading edge of a cutting tool (such as a lathe tool, drill, or milling cutter) where a line of contact is made with the work during machining.
- **cutting fluid**
  - A fluid used in metal cutting to improve finish, tool life, or dimensional accuracy. On being flowed over the tool and work, the fluid reduces friction, the heat generated, and tool wear, and prevents galling. It conducts the heat away from the point of generation and also serves to wash the chips away.
- **cutting speed**
  - The linear or peripheral speed of relative motion between the tool and workpiece in the principal direction of cutting.
- **cutting tip**
  - That part of an oxygen cutting torch from which the gases issue.
- **cutting torch (arc)**
  - A device used in air carbon arc cutting, gas tungsten arc cutting, and plasma arc cutting to control the position of the electrode, to transfer current, and to control the flow of gases.
- **cutting torch (oxyfuel gas)**
  - A device used for directing the preheating flame produced by the controlled combustion of fuel gases and to direct and control the cutting oxygen.
- **cyanic copper**
  - Copper electrodeposited from an alkali-cyanide solution containing a complex ion made up of univalent copper and the cyanide radical; also the solution itself.
- **cyanide slimes**
  - Finely divided metallic precipitates that are formed when precious metals are extracted from their ores using cyanide solutions.
- **cyaniding**
  - A case-hardening process in which a ferrous material is heated above the lower transformation temperature range in a molten salt containing cyanide to cause simultaneous absorption of carbon and nitrogen at the surface and, by diffusion, create a concentration gradient. Quench hardening completes the process.

- **cycle (*N*)**
  - In fatigue, one complete sequence of values of applied load that is repeated periodically. See also *S*-*N* curve .
- **cycle annealing**
  - An annealing process employing a predetermined and closely controlled time-temperature cycle to produce specific properties or microstructures.
- **cyclic load**
  - (1) Repetitive loading, as with regularly recurring stresses on a part, that sometimes leads to fatigue fracture. (2) Loads that change value by following a regular repeating sequence of change.
- **cylindrical grinding**
  - Grinding the outer cylindrical surface of a rotating part.
- **cylindrical land**
  - Land having zero relief.
- **D**
- **damage tolerance**
  - (1) A design measure of crack growth rate. Cracks in damage-tolerant designed structures are not permitted to grow to critical size during expected service life. (2) The ability of a part component, such as an aerospace engine, to resist failure due to the presence of flaws, cracks, or other damage for a specified period of usage. The damage tolerance approach is used extensively in the aerospace industry.
- **damping**
  - The loss in energy, as dissipated heat, that results when a material or material system is subjected to an oscillatory load or displacement.
- **damping capacity**
  - The ability of a material to absorb vibration (cyclical stresses) by internal friction, converting the mechanical energy into heat.
- **daylight**
  - The distance, in the open position, between the moving and the fixed tables or the platens of a hydraulic press. In the case of a multiplaten press, daylight is the distance between adjacent platens. Daylight provides space for removal of the molded/formed part from the mold/die.
- **dc casting**
  - Same as direct chill casting .
- **dead soft**
  - A temper of nonferrous alloys and some ferrous alloys corresponding to the condition of minimum hardness and tensile strength produced by full annealing.
- **dealloying**
  - The selective corrosion of one or more components of a solid solution alloy. Also called parting or selective leaching . See also decarburization , decobaltification , denickelification , dezincification , and graphitic corrosion .
- **deburring**
  - Removing burrs, sharp edges, or fins from metal parts by filing, grinding, or rolling the work in a barrel containing abrasives suspended in a suitable liquid medium. Sometimes called burring.
- **decalescence**
  - A phenomenon, associated with the transformation of αiron to γiron on the heating (superheating) of iron or steel, revealed by the darkening of the metal surface owing to the sudden decrease in temperature caused by the fast absorption of the latent heat of transformation. Contrast with recalescence .
- **decarburization**
  - Loss of carbon from the surface layer of a carbon-containing alloy due to reaction with one or more chemical substances in a medium that contacts the surface.
- **decobaltification**
  - Corrosion in which cobalt is selectively leached from cobalt-base alloys or from cemented carbides with cobalt binders. See also dealloying and selective leaching .
- **decohesive rupture**
  - A brittle fracture that exhibits little or no bulk plastic deformation and does not occur by dimple rupture, cleavage, or fatigue. This type of fracture is generally the result of a reactive

environment or a unique microstructure and is associated almost exclusively with rupture along grain boundaries.

- **decomposition**
  - Separation of a compound into its chemical elements or components.
- **decomposition potential (or voltage)**
  - The potential of a metal surface necessary to decompose the electrolyte of a cell or a component thereof.
- **deep drawing**
  - Forming deeply recessed parts by forcing sheet metal to undergo plastic flow between dies, usually without substantial thinning of the sheet.
- **deep etching**
  - In metallography, macroetching, especially for steels, to determine the overall character of the material, that is, the presence of imperfections, such as seams, forging bursts, shrinkage-void remnants, cracks, and coring.
- **defect**
  - (1) A discontinuity whose size, shape, orientation, or location makes it detrimental to the useful service of the part in which it occurs. (2) A discontinuity or discontinuities which by nature or accumulated effect (for example, total crack length) render a part or product unable to meet minimum applicable acceptance standards or specifications. This term designates rejectability. See also discontinuity and flaw .
- **defective**
  - A quality control term, describing a unit of product or service containing at least one defect , or having several lesser imperfections that, in combination, cause the unit not to fulfill its anticipated function.
- **deflection**
  - In metalforming and forging, the amount of deviation from a straight line or plane when a force is applied to a press member. Generally used to specify the allowable bending of the bed, slide, or frame at rated capacity with a load of predetermined distribution.
- **deformation**
  - A change in the form of a body due to stress, thermal change, change in moisture, or other causes. Measured in units of length.
- **deformation bands**
  - Parts of a crystal that have rotated differently during deformation to produce bands of varied orientation without individual grains.
- **deformation limit**
  - In drawing, the limit of deformation is reached when the load required to deform the flange becomes greater than the load-carrying capacity of the cup wall. The deformation limit (limiting drawing ratio, LDR) is defined as the ratio of the maximum blank diameter that can be drawn into a cup without failure, to the diameter of the punch.
- **degasifier**
  - A substance that can be added to molten metal to remove soluble gases that might otherwise be occluded or entrapped in the metal during solidification.
- **degassing**
  - (1) A chemical reaction resulting from a compound added to molten metal to remove gases from the metal. Inert gases are often used in this operation. (2) A fluxing procedure used for aluminum alloys in which nitrogen, chlorine, chlorine and nitrogen, and chlorine and argon are bubbled up through the metal to remove dissolved hydrogen gases and oxides from the alloy. See also flux .
- **degradation**
  - A deleterious change in the chemical structure, physical properties, or appearance of a material.
- **degreasing**
  - The removal of grease and oils from a surface. Can be accomplished by immersion in liquid organic solvent, by solvent vapors condensing on the parts being cleaned (vapor degreasing), or by spraying the parts with solvent.
- **delayed yield**
  - A phenomenon involving a delay in time between the application of a stress and the occurrence of the corresponding yield-point strain.
- **delta ferrite**
  - See ferrite .

- **Demarest process**
    - A fluid forming process in which cylindrical and conical sheet metal parts are formed by a modified rubber bulging punch. The punch, equipped with a hydraulic cell, is placed inside the workpiece, which in turn is placed inside the die. Hydraulic pressure expands the punch.
- **dendrite**
    - A crystal that has a treelike branching pattern, being most evident in cast metals slowly cooled through the solidification range.
- **dendritic powder**
    - Particles usually of electrolytic origin typically having the appearance of a pine tree.
- **denickelification**
    - Corrosion in which nickel is selectively leached from nickel-containing alloys. Most commonly observed in copper-nickel alloys after extended service in fresh water. See also dealloying and selective leaching .
- **density, absolute**
    - The mass per unit volume of a solid material, expressed in g/cm^3, kg/m^3, or lb/ft^3.
- **density ratio**
    - The ratio of the determined density of a powder compact to the absolute density of metal of the same composition, usually expressed as a percentage. Also referred to as percent theoretical density.
- **deoxidation**
    - Removal of excess oxygen from the molten metal; usually accomplished by adding materials with a high affinity for oxygen.
- **deoxidation products**
    - Those nonmetallic inclusions that form as a result of adding deoxidizing agents to molten metal.
- **deoxidized copper**
    - Copper from which cuprous oxide has been removed by adding a deoxidizer , such as phosphorus, to the molten bath.
- **deoxidizer**
    - A substance that can be added to molten metal to remove either free or combined oxygen.
- **deoxidizing**
    - (1) The removal of oxygen from molten metals through the use of a suitable deoxidizer. (2) Sometimes refers to the removal of undesirable elements other than oxygen through the introduction of elements or compounds that readily react with them. (3) In metal finishing, the removal of oxide films from metal surfaces by chemical or electrochemical reaction.
- **dephosphorization**
    - The elimination of phosphorus from molten steel.
- **depolarization**
    - A decrease in the polarization of an electrode.
- **deposit corrosion**
    - Corrosion occurring under or around a discontinuous deposit on a metallic surface. Also called poultice corrosion.
- **deposition efficiency (arc welding)**
    - The ratio of the weight of deposited metal to the net weight of filler metal consumed, exclusive of stubs.
- **deposition sequence**
    - The order in which the increments of weld metal are deposited.
- **depth of cut**
    - The thickness of material removed from a workpiece in a single machining part.
- **depth of fusion**
    - The distance that fusion extends into the base metal or previous pass from the surface melted during welding.
- **descaling**
    - (1) Removing the thick layer of oxides formed on some metals at elevated temperatures. (2) A chemical or mechanical process for removing scale or investment material from castings.
- **desulfurizing**
    - The removal of sulfur from molten metal by reaction with a suitable slag or by the addition of suitable compounds.

- **detonation flame spraying**
  - A thermal spraying process variation in which the controlled explosion of a mixture of fuel gas, oxygen, and powdered coating material is utilized to melt and propel the material to the workpiece.
- **detritus**
  - See wear debris .
- **developed blank**
  - A sheet metal blank that yields a finished part without trimming or with the least amount of trimming.
- **dewaxing**
  - In casting, the process of removing the expendable wax pattern from an investment mold or shell mold; usually accomplished by melting out the application of heat or dissolving the wax with an appropriate solvent.
- **dezincification**
  - Corrosion in which zinc is selectively leached from zinc-containing alloys leaving a relatively weak layer of copper and copper oxide. Most commonly found in copper-zinc alloys containing less than 85% Cu after extended service in water containing dissolved oxygen. See also dealloying and selective leaching .
- **diamagnetic material**
  - A material whose specific permeability is less than unity and is therefore repelled weakly by a magnet. Compare with ferromagnetic material and paramagnetic material .
- **diamond pyramid hardness test**
  - See Vickers hardness test .
- **diamond tool**
  - (1) A diamond, shaped or formed to the contour of a single-point cutting tool, for use in precision machining of nonferrous or nonmetallic materials. (2) An insert made from polycrystalline diamond compacts.
- **diamond wheels**
  - A grinding wheel in which crushed and sized industrial diamonds are held in a resinoid, metal, or vitrified bond.
- **diaphragm**
  - (1) A porous or permeable membrane separating anode and cathode compartments of an electrolytic cell from each other or from an intermediate compartment. (2) Universal die member made of rubber or similar material used to contain hydraulic fluid within the forming cavity and to transmit pressure to the part being formed.
- **dichromate treatment**
  - A chromate conversion coating produced on magnesium alloys in a boiling solution of sodium dichromate.
- **didymium**
  - A natural mixture of the rare-earth elements praseodymium and neodymium, often given the quasi-chemical symbol Di.
- **die**
  - A tool, usually containing a cavity, that imparts shape to solid, molten, or powdered metal primarily because of the shape of the tool itself. Used in many press operations (including blanking, drawing, forging, and forming), in die casting, and in forming green powder metallurgy compacts. Die-casting and powder metallurgy dies are sometimes referred to as molds . See also forging dies .
- **die block**
  - A block, often made of heat-treated steel, into which desired impressions are machined or sunk and from which closed-die forgings or sheet metal stampings are produced using hammers or presses. In forging, die blocks are usually used in pairs, with part of the impression in one of the blocks and the rest of the impression in the other. In sheet metal forming, the female die is used in conjunction with a male punch. See also closed-die forging .
- **die body**
  - The stationary or fixed part of a powder pressing die.
- **die casting**

  - (1) A casting made in a die. (2) A casting process in which molten metal is forced under high pressure into the cavity of a metal mold. See also cold chamber machine and hot chamber machine .
- **die cavity**
  - The machined recess that gives a forging or stamping its shape.
- **die clearance**
  - Clearance between a mated punch and die; commonly expressed as clearance per side. Also called clearance or punch-to-die clearance.
- **die cushion**
  - A press accessory placed beneath or within a bolster plate or die block to provide an additional motion or pressure for stamping or forging operations; actuated by air, oil, rubber, springs, or a combination of these.
- **die forging**
  - A forging that is formed to the required shape and size through working in machined impressions in specially prepared dies.
- **die forming**
  - The shaping of solid or powdered metal by forcing it into or through the die cavity.
- **die holder**
  - A plate or block, on which the die block is mounted, having holes or slots for fastening to the bolster plate or the bed of the press.
- **die impression**
  - The portion of the die surface that shapes a forging or sheet metal part.
- **die insert**
  - A relatively small die that contains part or all of the impression of a forging or sheet metal part and is fastened to the master die block.
- **die life**
  - The productive life of a die impression, usually expressed as the number of units produced before the impression has worn beyond permitted tolerances.
- **die lubricant**
  - (1) A lubricant applied to the working surfaces of dies and punches to facilitate drawing, pressing, stamping, and/or ejection. In powder metallurgy, the die lubricant is sometimes mixed into the powder before pressing into a compact. (2) A compound that is sprayed, swabbed, or otherwise applied on die surfaces or the workpiece during the forging or forming process to reduce friction. Lubricants also facilitate release of the part from the dies and provide thermal insulation. See also lubricant .
- **die match**
  - The condition where dies, after having been set up in a press or other equipment, are in proper alignment relative to each other.
- **die opening**
  - (1) In flash or upset welding, the distance between the electrodes, usually measured with the parts in contact before welding has commenced or immediately upon completion of the cycle but before upsetting. (2) In powder metallurgy, the entrance to the die cavity.
- **die proof**
  - A casting of a die impression made to confirm the accuracy of the impression.
- **die radius**
  - The radius on the exposed edge of a deep-drawing die, over which the sheet flows in forming drawn shells.
- **die set**
  - A tool or tool holder consisting of a die base and punch plate for the attachment of a die and punch, respectively.
- **die shift**
  - The condition that occurs after the dies have been set up in a forging unit in which a portion of the impression of one die is not in perfect alignment with the corresponding portion of the other die. This results in a mismatch in the forging, a condition that must be held within the specified tolerance.
- **die sinking**
  - The machining of the die impressions to produce forgings of required shapes and dimensions.
- **die stamping**

  - The general term for a sheet metal part that is formed, shaped, or cut by a die in a press in one or more operations.
- **die welding**
  - See preferred terms forge welding and cold welding .
- **differential aeration cell**
  - An electrolytic cell, the electromagnetic force of which is due to a difference in air (oxygen) concentration at one electrode as compared with that at another electrode of the same material. See also concentration cell .
- **differential coating**
  - A coated product having a specified coating on one surface and a significantly lighter coating on the other surface (such as a hot dip galvanized product or electrolytic tin plate).
- **differential floatation**
  - Separating a complex ore into two or more valuable minerals and gangue by flotation. Also called selective flotation.
- **differential heating**
  - Heating that intentionally produces a temperature gradient within an object such that, after cooling, a desired stress distribution or variation in properties is present within the object.
- **diffusion**
  - (1) Spreading of a constituent in a gas, liquid, or solid, tending to make the composition of all parts uniform. (2) The spontaneous movement of atoms or molecules to new sites within a material.
- **diffusion aid**
  - A solid filler metal sometimes used in diffusion welding .
- **diffusion bonding**
  - See preferred terms diffusion welding and diffusion brazing .
- **diffusion brazing**
  - A brazing process that produces coalescence of metals by heating them to suitable temperatures and by using a filler metal or an in situ liquid phase. The filler metal may be distributed by capillary action or may be placed or formed at the faying surfaces. The filler metal is diffused with the base metal to the extent that the joint properties have been changed to approach those of the base metal. Pressure may or may not be applied.
- **diffusion coating**
  - Any process whereby a base metal or alloy is either (1) coated with another metal or alloy and heated to a sufficient temperature in a suitable environment or (2) exposed to a gaseous or liquid medium containing the other metal or alloy, thus causing diffusion of the coating or of the other metal or alloy into the base metal with resultant changes in the composition and properties of its surface.
- **diffusion coefficient**
  - A factor of proportionality representing the amount of substance diffusing across a unit area through a unit concentration gradient in unit time.
- **diffusion welding**
  - A solid-state welding process that produces coalescence of the faying surfaces by the application of pressure at elevated temperature. The process does not involve macroscopic deformation, melting, or relative motion of parts. A solid filler metal (diffusion aid) may or may not be inserted between the faying surfaces. See also forge welding , hot pressure welding , and cold welding .
- **dilatometer**
  - An instrument for measuring the linear expansion or contraction in a metal resulting from changes in such factors as temperature and allotropy.
- **dimple rupture**
  - A fractographic term describing ductile fracture that occurs through the formation and coalescence of microvoids along the fracture path. The fracture surface of such a ductile fracture appears dimpled when observed at high magnification and usually is most clearly resolved when viewed in a scanning electron microscope.
- **dimpling**
  - (1) The stretching of a relatively small, shallow indentation into sheet metal. (2) In aircraft, the stretching of metal into a conical flange for a countersunk head rivet.
- **dip brazing**

  - A brazing process in which the heat required is furnished by a molten chemical or metal bath. When a molten chemical bath is used, the bath may act as a flux . When a molten metal bath is used, the bath provides the filler metal.
- **dip coat**
  - (1) In the solid mold technique of investment casting, an extremely fine ceramic precoat applied as a slurry directly to the surface of the pattern to reproduce maximum surface smoothness. This coating is surrounded by coarser, less expensive, and more permeable investment to form the mold. (2) In the shell mold technique of investment casting, an extremely fine ceramic coating called the first coat, applied as a slurry directly to the surface of the pattern to reproduce maximum surface smoothness. The first coat is followed by other dip coats of different viscosity and usually containing different grading of ceramic particles. After each dip, coarser stucco material is applied to the still-wet coating. A buildup of several coats forms an investment shell mold. See also investment casting .
- **diphase cleaning**
  - Removing soil by an emulsion that produces two phases in the cleaning tank: a solvent phase and an aqueous phase. Cleaning is effected by both solvent action and emulsification.
- **dip plating**
  - Same as immersion plating .
- **dip soldering**
  - A soldering process in which the heat required is furnished by a molten metal bath that provides the solder filler metal.
- **direct chill casting**
  - A continuous method of making ingots for rolling or extrusion by pouring the metal into a short mold. The base of the mold is a platform that is gradually lowered while the metal solidifies, the frozen shell of metal acting as a retainer for the liquid metal below the wall of the mold. The ingot is usually cooled by the impingement of water directly on the mold or on the walls of the solid metal as it is lowered. The length of the ingot is limited by the depth to which the platform can be lowered; therefore, it is often called semicontinuous casting.
- **direct current arc furnace**
  - An electric arc furnace in which a single electrode positioned at the center of the furnace roof is the cathode of the system. Current passes from the electrode through the charge or bath to a cathode located at the bottom of the furnace. Current from the bottom of the furnace then passes through the furnace refractories to a copper base plate to outside cables. Used in the production of ferroalloys, carbon and alloy steels, and stainless steels. See also arc furnace .
- **direct current electrode negative (DCEN)**
  - The arrangement of direct current arc welding leads in which the work is the positive pole and the electrode is the negative pole of the welding arc. Also referred to as straight polarity.
- **direct current electrode positive (DCEP)**
  - The arrangement of direct current arc welding leads in which the work is the negative pole and the electrode is the positive pole of the welding arc. Also referred to as reverse polarity.
- **direct current reverse polarity (DCRP)**
  - See direct current electrode positive .
- **direct current straight polarity (DCSP)**
  - See direct current electrode negative .
- **direct (forward) extrusion**
  - See extrusion .
- **directional property**
  - Property whose magnitude varies depending on the relation of the test axis to a specific direction within the metal. The variation results from preferred orientation or from fibering of constituents or inclusions.
- **directional solidification**
  - Controlled solidification of molten metal in a casting so as to provide feed metal to the solidifying front of the casting.
- **direct quenching**
  - (1) Quenching carburized parts directly from the carburizing operation. (2) Also used for quenching pearlitic malleable parts directly from the malleabilizing operation.
- **discontinuity**

    - (1) Any interruption in the normal physical structure or configuration of a part, such as cracks, laps, seams, inclusions, or porosity. A discontinuity may or may not affect the utility of the part. (2) An interruption of the typical structure of a weldment, such as a lack of homogeneity in the mechanical, metallurgical, or physical characteristics of the material or weldment. A discontinuity is not necessarily a defect. See also defect and flaw .
- **discontinuous precipitation**
    - Precipitation from a supersaturated solid solution in which the precipitate particles grow by short-range diffusion, accompanied by recrystallization of the matrix in the region of precipitation. Discontinuous precipitates grow into the matrix from nuclei near grain boundaries, forming cells of alternate lamellae of precipitate and depleted (and recrystallized) matrix. Often referred to as cellular or nodular precipitation. Compare with continuous precipitation and localized precipitation .
- **discontinuous yielding**
    - The nonuniform plastic flow of a metal exhibiting a yield point in which plastic deformation is inhomogeneously distributed along the gage length. Under some circumstances, it may occur in metals not exhibiting a distinct yield point, either at the onset of or during plastic flow.
- **dishing**
    - Forming a shallow concave surface, the area being large compared to the depth.
- **disk grinding**
    - Grinding with the flat side of an abrasive disk or segmented wheel. Also called vertical-spindle surface grinding.
- **dislocation**
    - A linear imperfection in a crystalline array of atoms. Two basic types are recognized: (1) an edge dislocation corresponds to the row of mismatched atoms along the edge formed by an extra, partial plane of atoms within the body of a crystal; (2) a screw dislocation corresponds to the axis of a spiral structure in a crystal, characterized by a distortion that joins normally parallel planes together to form a continuous helical ramp (with a pitch of one interplanar distance) winding about the dislocation. Most prevalent is the so-called mixed dislocation, which is any combination of an edge dislocation and a screw dislocation.
- **disordered structure**
    - The crystal structure of a solid solution in which the atoms of different elements are randomly distributed relative to the available lattice sites. Contrast with ordered structure .
- **disordering**
    - Forming a lattice arrangement in which the solute and solvent atoms of a solid solution occupy lattice sites at random. See also superlattice .
- **dispersing agent**
    - A substance that increases the stability of a suspension of particles in a liquid medium by deflocculation of the primary particles.
- **dispersion hardening**
    - See dispersion strengthening .
- **dispersion-strengthened material**
    - A metallic material that contains a fine dispersion of nonmetallic phase(s), such as Al_2O_3, MgO, SiO_2, CdO, ThO_2, Y_2O_3, or ZrO_2 singly or in combination, to increase the hot strength of the metallic matrix. Examples include dispersion-strengthened copper (Al_2O_3) used for welding electrodes, silver (CdO) used for electrical contacts, and nickel-chromium (Y_2O_3) superalloys used for gas turbine components. See also mechanical alloying .
- **dispersion strengthening**
    - The strengthening of a metal or alloy by incorporating chemically stable submicron size particles of a nonmetallic phase that impede dislocation movement at elevated temperature.
- **dispersoid**
    - Finely divided particles of relatively insoluble constituents visible in the microstructure of certain metallic alloys.
- **distortion**
    - Any deviation from an original size, shape, or contour that occurs because of the application of stress or the release of residual stress.
- **disturbed metal**
    - The cold-worked metal layer formed at a polished surface during the process of mechanical grinding and polishing.

- **divided cell**
    - A cell containing a diaphragm or other means for physically separating the anolyte from the catholyte .
- **divorced eutectic**
    - A metallographic appearance in which the two constituents of a eutectic structure appear as massive phases rather than the finely divided mixture characteristic of normal eutectics. Often, one of the constituents of the eutectics is continuous and indistinguishable from an accompanying proeutectic constituent.
- **domain, magnetic**
    - A substructure in a ferromagnetic material within which all the elementary magnets (electron spins) are held aligned in one direction by interatomic forces; if isolated, a domain would be a saturated permanent magnet.
- **double-acting hammer**
    - A forging hammer in which the ram is raised by admitting steam or air into a cylinder below the piston, and the blow intensified by admitting steam or air above the piston on the downward stroke.
- **double-action die**
    - A die designed to perform more than one operation in a single stroke of the press.
- **double-action forming**
    - Forming or drawing in which more than one action is achieved in a single stroke of the press.
- **double-action mechanical press**
    - A press having two independent parallel movements by means of two slides, one moving within the other. The inner slide or plunger is usually operated by a crankshaft; the outer or blankholder slide, which dwells during the drawing operation, is usually operated by a toggle mechanism or by cams. See also slide .
- **double aging**
    - Employment of two different aging treatments to control the type of precipitate formed from a supersaturated matrix in order to obtain the desired properties. The first aging treatment, sometimes referred to as intermediate or stabilizing, is usually carried out at higher temperature than the second.
- **double tempering**
    - A treatment in which a quench-hardened ferrous metal is subjected to two complete tempering cycles, usually at substantially the same temperature, for the purpose of ensuring completion of the tempering reaction and promoting stability of the resulting microstructure.
- **double-welded joint**
    - In arc and oxyfuel gas welding, any joint welded from both sides.
- **downgate**
    - Same as sprue .
- **downhand welding**
    - See flat-position welding .
- **down milling**
    - See preferred term climb milling .
- **downsprue**
    - Same as sprue .
- **Dow process**
    - A process for the production of magnesium by electrolysis of molten magnesium chloride.
- **draft**
    - (1) An angle or taper on the surface of a pattern, core box, punch, or die (or of the parts made with them) that facilitates removal of the parts from a mold or die cavity, or a core from a casting. (2) The change in cross section that occurs during rolling or cold drawing.
- **drag**
    - The bottom section of a flask , mold , or pattern .
- **drag**
    - (thermal cutting). The offset distance between the actual and the theoretical exit points of the cutting oxygen stream measured on the exit surface of the material.
- **drawability**
    - A measure of the formability of a sheet metal subject to a drawing process. The term is usually used to indicate the ability of a metal to be deep drawn. See also drawing and deep drawing .

- **draw bead**
  - An insert or riblike projection on the draw ring or hold-down surfaces that aids in controlling the rate of metal flow during deep draw operations. Draw beads are especially useful in controlling the rate of metal flow in irregularly shaped stampings.
- **drawbench**
  - The stand that holds the die and draw head used in drawing of wire, rod, and tubing.
- **draw forging**
  - See radial forging .
- **draw forming**
  - A method of curving bars, tubes, or rolled or extruded sections in which the stock is bent around a rotating form block. Stock is bent by clamping it to the form block, then rotating the form block while the stock is pressed between the form block and a pressure die held against the periphery of the form block.
- **draw head**
  - Set of rolls or dies mounted on a drawbench for forming a section from strip, tubing, or solid stock. See also Turk's-head rolls .
- **drawing**
  - A term used for a variety of forming operations, such as deep drawing a sheet metal blank; redrawing a tubular part; and drawing rod, wire, and tube. The usual drawing process with regard to sheet metal working in a press is a method for producing a cuplike form from a sheet metal disk by holding it firmly between blankholding surfaces to prevent the formation of wrinkles while the punch travel produces the required shape.
- **drawing compound**
  - (1) A substance applied to prevent pickup and scoring during drawing or pressing operations by preventing metal-to-metal contact of the work and die. Also known as die lubricant . (2) In metalworking, a lubricant having extreme-pressure properties. See also extreme-pressure lubricant .
- **drawing out**
  - A stretching operation resulting from forging a series of upsets along the length of the workpiece.
- **draw marks**
  - See scoring , galling , and pickup .
- **drawn shell**
  - An article formed by drawing sheet metal into a hollow structure having a predetermined geometrical configuration.
- **draw plate**
  - (1) In metalforming, a circular plate with a hole in the center contoured to fit a forming punch; used to support the blank during the forming cycle. (2) In casting, a plate attached to a pattern to facilitate drawing of a pattern from the mold.
- **draw radius**
  - The radius at the edge of a die or punch over which sheet metal is drawn.
- **draw ring**
  - A ring-shaped die part (either the die ring itself or a separate ring) over which the inner edge of sheet metal is drawn by the punch.
- **draw stock**
  - The forging operation in which the length of a metal mass (stock) is increased at the expense of its cross section; no upset is involved. The operation includes converting ingot to pressed bar using "V," round, or flat dies.
- **dressing**
  - (1) Cutting, breaking down, or crushing the surface of a grinding wheel to improve its cutting ability and accuracy. (2) Removing dulled grains from the cutting face of a grinding wheel to restore cutting quality.
- **drift**
  - (1) A flat piece of steel of tapering width used to remove taper shank drills and other tools from their holders. (2) A tapered rod used to force mismated holes into line for riveting or bolting. Sometimes called a drift pin.
- **drilling**
  - Hole making with a rotary end-cutting tool having one or more cutting lips and one or more helical or straight flutes or tubes for the ejection of chips and the passage of a cutting fluid.

- **drop forging**
  - (1) The forging obtained by hammering metal in a pair of closed dies to produce the form in the finishing impression under a drop hammer. (2) Forging method requiring special dies for each shape.
- **drop hammer**
  - A term generally applied to forging hammers in which energy for forging is provided by gravity, steam, or compressed air. See also air-lift hammer , board hammer , and steam hammer .
- **drop hammer forming**
  - A process for producing shapes by the progressive deformation of sheet metal in matched dies under the repetitive blows of a gravity-drop or power-drop hammer. The process is restricted to relatively shallow parts and thin sheet from approximately 0.6 to 1.6 mm (0.024 to 0.064 in.).
- **droplet erosion**
  - Erosive wear caused by the impingement of liquid droplets on a solid surface. See also erosion .
- **drop-through**
  - An undesirable sagging or surface irregularity, usually encountered when brazing or welding near the solidus of the base metal, caused by overheating with rapid diffusion or alloying between the filler metal and the base metal.
- **dross**
  - (1) The scum that forms on the surface of molten metal largely because of oxidation but sometimes because of the rising of impurities to the surface. (2) Oxide and other contaminants that form on the surface of molten solder.
- **dry corrosion**
  - See gaseous corrosion .
- **dry cyaniding (obsolete)**
  - Same as carbonitriding .
- **dry sand mold**
  - A casting mold made of sand and then dried at 100 °C (212 °F) or above before being used. Contrast with green sand mold .
- **dry strength (casting)**
  - The maximum strength of a molded sand specimen that has been thoroughly dried at 100 to 110 °C (220 to 230 °F) and cooled to room temperature. Also known as dry bond strength.
- **dual-phase steels**
  - A class of high-strength low-alloy steels characterized by a tensile strength value of approximately 550 MPa (80 ksi) and by a microstructure consisting of about 20% hard martensite particles dispersed in a soft ductile ferrite matrix. The term dual phase refers to the predominance in the microstructure of two phases, ferrite and martensite. However, small amounts of other phases, such as bainite, pearlite, or retained austenite, may also be present.
- **ductile crack propagation**
  - Slow crack propagation that is accompanied by noticeable plastic deformation and requires energy to be supplied from outside the body. Contrast with brittle crack propagation .
- **ductile fracture**
  - Fracture characterized by tearing of metal accompanied by appreciable gross plastic deformation and expenditure of considerable energy. Contrast with brittle fracture .
- **ductile iron**
  - A cast iron that has been treated while molten with an element such as magnesium or cerium to induce the formation of free graphite as nodules or spherulites, which imparts a measurable degree of ductility to the cast metal. Also known as nodular cast iron, spherulitic graphite cast iron, and spheroidal graphite (SG) iron.
- **ductility**
  - The ability of a material to deform plastically without fracturing.
- **dummy block**
  - In extrusion, a thick unattached disk placed between the ram and the billet to prevent overheating of the ram.
- **dummy cathode**
  - (1) A cathode, usually corrugated to give variable current densities, that is plated at low current densities to preferentially remove impurities from a plating solution. (2) A substitute cathode that is used during adjustment of operating conditions.
- **duplex grain size**

  - The simultaneous presence of two grain sizes in substantial amounts, with one grain size appreciably larger than the others. Also termed mixed grain size.
- **duplexing**
  - Any two-furnace melting or refining process. Also called duplex melting or duplex processing.
- **duplex microstructure**
  - A two-phase structure.
- **duplex stainless steels**
  - Stainless steels having a fine-grained mixed microstructure of ferrite and austenite with a composition centered around 26Cr-6.5Ni.
- **duralumin (obsolete)**
  - A term frequently applied to the class of age-hardenable aluminum-copper alloys containing manganese, magnesium, or silicon.
- **dusting**
  - (1) A phenomenon, usually affecting carbon-base electrical motor brushes or other current-carrying contacts, wherein at low relative humidity or high applied current density, a powdery "dust" is produced during operation. (2) Applying a powder, such as sulfur to molten magnesium or graphite to a mold surface.
- **dynamic**
  - Moving, or having high velocity. Frequently used with high strain rate ($>0.1\ s^{-1}$) testing of metal specimens.
- **dynamic creep**
  - Creep that occurs under conditions of fluctuating load or fluctuating temperature.
- **E**
- **earing**
  - The formation of ears or scalloped edges around the top of a drawn shell, resulting from directional differences in the plastic-working properties of rolled metal, with, across, or at angles to the direction of rolling.
- **eccentric press**
  - A mechanical press in which an eccentric, instead of a crankshaft, is used to move the slide.
- **ECM**
  - An abbreviation for electrochemical machining .
- **eddy-current testing**
  - An electromagnetic nondestructive testing method in which eddy-current flow is induced in the test object. Changes in flow caused by variations in the object are reflected into a nearby coil or coils where they are detected and measured by suitable instrumentation.
- **edge dislocation**
  - See dislocation .
- **edger (edging impression)**
  - The portion of a die impression that distributes metal during forging into areas where it is most needed in order to facilitate filling the cavities of subsequent impressions to be used in the forging sequence. See also fuller (fullering impression) .
- **edge strain**
  - Transverse strain lines or Lüders lines ranging from 25 to 300 mm (1 to 12 in.) in from the edges of cold rolled steel sheet or strip. See also Lüders lines .
- **edging**
  - (1) In sheet metal forming, reducing the flange radius by retracting the forming punch a small amount after the stroke but before release of the pressure. (2) In rolling, the working of metal in which the axis of the roll is parallel to the thickness dimension. Also called edge rolling. (3) The forging operation of working a bar between contoured dies while turning it 90° between blows to produce a varying rectangular cross section. (4) In a forging, removing flash that is directed upward between dies, usually accomplished using a lathe.
- **EDM**
  - Abbreviation for electrical discharge machining .
- **effective crack size**
  - The physical crack size augmented for the effects of crack tip plastic deformation. Sometimes the effective crack size is calculated from a measured value of a physical crack size plus a calculated value of a plastic zone adjustment. A preferred method for calculation of effective crack size

    - compares compliance from the secant of a load-deflection trace with the elastic compliance from a calibration for the type of specimen.
- **effective draw**
    - The maximum limits of forming depth that can be achieved with a multiple-action press; sometimes called maximum draw or maximum depth of draw.
- **885 °F (475 °C) embrittlement**
    - Embrittlement of stainless steels upon extended exposure to temperatures between 400 and 510 °C (750 and 950 °F). This type of embrittlement is caused by fine, chromium-rich precipitates that segregate at grain boundaries; time at temperature directly influences the amount of segregation. Grain-boundary segregation of the chromium-rich precipitates increases strength and hardness, decreases ductility and toughness, and changes corrosion resistance. This type of embrittlement can be reversed by heating above the precipitation range.
- **ejector**
    - A device mounted in such a way that it removes or assists in removing a formed part from a die.
- **ejector half**
    - The movable half of a die-casting die containing the ejector pins.
- **ejector rod**
    - A rod used to push out a formed piece.
- **elastic constants**
    - The factors of proportionality that relate elastic displacement of a material to applied forces. See also bulk modulus of elasticity , modulus of elasticity , Poisson's ratio , and shear modulus .
- **elastic deformation**
    - A change in dimensions directly proportional to and in phase with an increase or decrease in applied force.
- **elastic hysteresis**
    - A misnomer for an anelastic strain that lags a change in applied stress, thereby creating energy loss during cyclic loading. More properly termed mechanical hysteresis .
- **elasticity**
    - The property of a material by virtue of which deformation caused by stress disappears upon removal of the stress. A perfectly elastic body completely recovers its original shape and dimensions after release of stress.
- **elastic limit**
    - The maximum stress that a material is capable of sustaining without any permanent strain (deformation) remaining upon complete release of the stress. A material is said to have passed its elastic limit when the load is sufficient to initiate plastic, or nonrecoverable, deformation. See also proportional limit .
- **elastic modulus**
    - Same as modulus of elasticity .
- **elastic ratio**
    - Yield point divided by tensile strength.
- **elastic strain**
    - See elastic deformation .
- **elastic strain energy**
    - The energy expended by the action of external forces in deforming a body elastically. Essentially all the work performed during elastic deformation is stored as elastic energy, and this energy is recovered upon release of the applied force.
- **electrical discharge grinding**
    - Grinding by spark discharges between a negative electrode grinding wheel and a positive workpiece separated by a small gap containing a dielectric fluid such as petroleum oil.
- **electrical discharge machining (EDM)**
    - Metal removed by a rapid spark discharge between different polarity electrodes, one on the workpiece and the other the tool separated by a gap distance of 0.013 to 0.9 mm (0.0005 to 0.035 in.). The gap is filled with dielectric fluid and metal particles that are melted, in part vaporized, and expelled from the gap.
- **electrical discharge wire cutting**
    - A special form of electrical discharge machining wherein the electrode is a continuous moving conductive wire. Also referred to as traveling wire electrical discharge machining.
- **electrical disintegration**

    - Metal removal by an electrical spark acting in air. It is not subject to precise control, the most common application being the removal of broken tools such as taps and drills.
- **electrical pitting**
    - The formation of surface cavities by removal of metal as a result of an electrical discharge across an interface.
- **electric arc furnace**
    - See arc furnace .
- **electric arc spraying**
    - See preferred term arc spraying .
- **electric furnace**
    - A metal melting or holding furnace that produces heat from electricity. It may operate on the resistance or induction principle. See also induction furnace .
- **electrochemical cell**
    - An electrochemical system consisting of an anode and a cathode in metallic contact and immersed in an electrolyte. The anode and cathode may be different metals or dissimilar areas on the same metal surface. See also cathodic protection .
- **electrochemical corrosion**
    - Corrosion that is accompanied by a flow of electrons between cathodic and anodic areas on metallic surfaces.
- **electrochemical discharge machining**
    - Metal removal by a combination of the processes of electrochemical machining and electrical discharge machining. Most of the metal removal occurs via anodic dissolution (i.e., ECM action). Oxide films which form as a result of electrolytic action through an electrolytic fluid are removed by intermittent spark discharges (i.e., EDM action). Hence, the combination of the two actions.
- **electrochemical equivalent**
    - The weight of an element or group of elements oxidized or reduced at 100% efficiency by the passage of a unit quantity of electricity. Usually expressed as grams per coulomb.
- **electrochemical grinding**
    - A process whereby metal is removed by deplating. The workpiece is the anode; the cathode is a conductive aluminum oxide-copper or metal-bonded diamond grinding wheel with abrasive particles. Most of the metal is removed by deplating; 0.05 to 10% is removed by abrasive cutting.
- **electrochemical machining (ECM)**
    - Controlled metal removal by anodic dissolution. Direct current passes through flowing film of conductive solution which separates the workpiece from the electrode tool. The workpiece is the anode, and the tool is the cathode.
- **electrochemical potential**
    - The partial derivative of the total electrochemical free energy of a constituent with respect to the number of moles of this constituent where all factors are kept constant. It is analogous to the chemical potential of a constituent except that it includes the electric as well as chemical contributions to the free energy. The potential of an electrode in an electrolyte relative to a reference electrode measured under open circuit conditions.
- **electrochemical reaction**
    - A reaction caused by passage of an electric current through a medium that contains mobile ions (as in electrolysis); or, a spontaneous reaction made to cause current to flow in a conductor external to this medium (as in a galvanic cell). In either event, electrical connection is made to the external portion of the circuit via a pair of electrodes. See also electrolyte .
- **electrochemical series**
    - Same as electromotive force series .
- **electrode**
    - Compressed graphite or carbon cylinder or rod used to conduct electric current in electric arc furnaces, arc lamps, and so forth.
- **electrode (electrochemistry)**
    - One of a pair of conductors introduced into an electrochemical cell, between which the ions in the intervening medium flow in opposite directions and on whose surfaces reactions occur (when appropriate external connection is made). In direct current operation, one electrode or "pole" is positively charged, the other negatively. See also anode , cathode , electrochemical reaction , and electrolyte .
- **electrode (welding)**

  - (1) In arc welding, a current-carrying rod that supports the arc between the rod and work, or between two rods as in twin carbon-arc welding. It may or may not furnish filler metal. See also bare electrode , covered electrode , flux cored electrode , lightly coated electrode , metal cored electrode , metal electrode , and stranded electrode . (2) In resistance welding, a part of a resistance welding machine through which current and, in most instances, pressure are applied directly to the work. The electrode may be in the form of a rotating wheel, rotating roll, bar, cylinder, plate, clamp, chuck, or modification thereof. (3) In arc and plasma spraying, the current-carrying components that support the arc.
- **electrode cable**
  - Same as electrode lead .
- **electrode deposition**
  - The weight of weld-metal deposit obtained from a unit length of electrode.
- **electrode extension**
  - For gas metal arc welding, flux cored arc welding, and submerged arc welding, the length of unmelted electrode extending beyond the end of the contact tube.
- **electrode force**
  - The force between electrodes in a spot, seam, and projection weld.
- **electrode holder**
  - A device used for mechanically holding the electrode while conducting current to it.
- **electrode indentation (resistance welding)**
  - The depression formed on the surface of workpieces by electrodes.
- **electrode lead**
  - The electrical conductor between the source of arc welding current and the electrode holder.
- **electrode polarization**
  - Change of electrode potential with respect to a reference value. The change may be caused, for example, by the application of an external electrical current or by the addition of an oxidant or reductant.
- **electrodeposition**
  - (1) The deposition of a conductive material from a plating solution by the application of electrical current. (2) The deposition of a substance on an electrode by passing electric current through an electrolyte. Electroplating, electroforming, electrorefining, and electrotwinning result from electrodeposition.
- **electrode potential**
  - The potential of an electrode in electrolysis as measured against a reference electrode. The electrode potential does not include any resistance losses in potential in either the solution or external circuit. It represents the reversible work to move a unit charge from the electrode surface through the solution to the reference electrode.
- **electrode reaction**
  - Interfacial reaction equivalent to a transfer of charge between electronic and ionic conductors. See also anodic reaction and cathodic reaction .
- **electroforming**
  - Making parts by electrodeposition on a removable form.
- **electrogalvanizing**
  - The electroplating of zinc upon iron or steel.
- **electrogas welding (EGW)**
  - An arc welding process that produces coalescence of metals by heating them with an arc between a continuous filler metal electrode and the work. Molding shoes are used to confine the molten weld metal for vertical position welding. The electrodes may either be flux cored or solid. Shielding may or may not be obtained from an externally supplied gas or mixture.
- **electroless plating**
  - (1) A process in which metal ions in a dilute aqueous solution are plated out on a substrate by means of autocatalytic chemical reduction. (2) The deposition of conductive material from an autocatalytic plating solution without the application of electrical current.
- **electrolysis**
  - (1) Chemical change resulting from the passage of an electric current through an electrolyte. (2) The separation of chemical components by the passage of current through an electrolyte.
- **electrolyte**

  - (1) A chemical substance or mixture, usually liquid, containing ions that migrate in an electric field. (2) A chemical compound or mixture of compounds which when molten or in solution will conduct an electric current.
- **electrolytic brightening**
  - Same as electropolishing .
- **electrolytic cell**
  - An assembly, consisting of a vessel, electrodes, and an electrolyte, in which electrolysis can be carried out.
- **electrolytic cleaning**
  - A process of removing soil, scale, or corrosion products from a metal surface by subjecting it as an electrode to an electric current in an electrolytic bath.
- **electrolytic copper**
  - Copper that has been refined by electrodeposition, including cathodes that are the direct product of the refining operation, refinery shapes cast from melted cathodes, and, by extension, fabricators' products made therefrom. Usually when this term is used alone, it refers to electrolytic tough pitch copper without elements other than oxygen being present in significant amounts. See also tough pitch copper .
- **electrolytic deposition**
  - Same as electrodeposition .
- **electrolytic grinding**
  - A combination of grinding and machining wherein a metal-bonded abrasive wheel, usually diamond, is the cathode in physical contact with the anodic workpiece, the contact being made beneath the surface of a suitable electrolyte. The abrasive particles that produce grinding act as nonconducting spacers permitting simultaneous machining through electrolysis.
- **electrolytic machining**
  - Controlled removal of metal using an applied potential and a suitable electrolyte to produce the shapes and dimensions desired.
- **electrolytic picking**
  - Pickling in which electric current is used, the work being one of the electrodes.
- **electrolytic polishing**
  - An electrochemical polishing process in which the metal to be polished is made the anode in an electrolytic cell where preferential dissolution at high points in the surface topography produces a specularly reflective surface. Also referred to as electropolishing .
- **electrolytic powder**
  - Powder produced by electrodeposition or by pulverizing of an electrodeposit.
- **electrolytic protection**
  - See preferred term cathodic protection .
- **electrolytic tough pitch**
  - A term describing the method of raw copper preparation to ensure a good physical- and electrical-grade copper-finished product.
- **electromagnetic forming**
  - A process for forming metal by the direct application of an intense, transient magnetic field. The workpiece is formed without mechanical contact by the passage of a pulse of electric current through a forming coil. Also known as magnetic pulse forming.
- **electromagnetic radiation**
  - Energy propagated at the speed of light by an electromagnetic field. The electromagnetic spectrum includes the following approximate wavelength regions:

Region	**Wavelength, Å (nm)**
Gamma-ray	0.005 to 1.40 (0.0005 to 0.14)
X-ray	0.1 to 100 (0.01 to 10)
Far-ultraviolet	100 to 2000 (10 to 200)
Near-ultraviolet	2000 to 3800 (200 to 380)

Visible	3800 to 7800 (380 to 780)
Near-infrared	7800 to 30,000 (0.78 to 3 μm)
Middle-infrared	3×10^4 to 3×10^5 (3 to 30 μm)
Far-infrared	3×10^5 to 3×10^6 (30 to 300 μm)
Microwave	3×10^6 to 1×10^{10} (0.3 mm to 1 m)

- **electromechanical polishing**
  - An attack-polishing method in which the chemical action of the polishing fluid is enhanced or controlled by the application of an electric current between the specimen and the polishing wheel.
- **electrometallurgy**
  - Industrial recovery or processing of metals and alloys by electric or electrolytic methods.
- **electromotive force**
  - (1) The force that determines the flow of electricity; a difference of electric potential. (2) Electrical potential; voltage.
- **electromotive force series (emf series)**
  - A series of elements arranged according to their standard electrode potentials, with "noble" metals such as gold being positive and "active" metals such as zinc being negative. In corrosion studies, the analogous but more practical galvanic series of metals is generally used. The relative positions of a given metal are not necessarily the same in the two series.
- **electron bands**
  - Energy states for the free electrons in a metal, as described by the use of the band theory (zone theory) of electron structure. Also called Brillouin zones.
- **electron beam cutting**
  - A cutting process that uses the heat obtained from a concentrated beam composed primarily of high-velocity electrons, which impinge on the workpieces to be cut; it may or may not use an externally supplied gas.
- **electron beam heat treating**
  - A selective surface hardening process that rapidly heats a surface by direct bombardment with an accelerated stream of electrons.
- **electron beam machining**
  - Removing material by melting and vaporizing the workpiece at the point of impingement of a focused high-velocity beam of electrons. The machining is done in high vacuum to eliminate scattering of the electrons due to interaction with gas molecules. The most important use of electron beam machining is for hole drilling.
- **electron beam welding (EBW)**
  - A welding process that produces coalescence of metals with the heat obtained from a concentrated beam composed primarily of high-velocity electrons impinging on the surfaces to be joined.
- **electrophoresis**
  - Transport of charged colloidal or macromolecular materials in an electric field.
- **electroplate**
  - The application of a metallic coating on a surface by means of electrolytic action.
- **electroplating**
  - The electrodeposition of an adherent metallic coating on an object serving as a cathode for the purpose of securing a surface with properties or dimensions different from those of the substrate.
- **electropolishing**
  - A technique commonly used to prepare metallographic specimens, in which a high polish is produced making the specimen the anode in an electrolytic cell, where preferential dissolution at high points smooths the surface. Also referred to as electrolytic polishing .
- **electrorefining**
  - Using electric or electrolytic methods to convert impure metal to purer metal, or to produce an alloy from impure or partly purified raw materials.
- **electroslag remelting (ESR)**
  - A consumable-electrode remelting process in which heat is generated by the passage of electric current through a conductive slag. The droplets of metal are refined by contact with the slag.
- **electroslag welding (ESW)**

  - A welding process that produces coalescence of metals with molten slag that melts the filler metal and the surfaces of the workpieces. The weld pool is shielded by this slag, which moves along the full cross section of the joint as welding progresses. The process is initiated by an arc that heats the slag. The arc is then extinguished by the conductive slag, which is kept molten by its resistance to electric current passing through the electrode and the workpieces.
- **electrostrictive effect**
  - The reversible interaction, exhibited by some crystalline materials, between an elastic strain and an electric field. The direction of the strain is independent of the polarity of the field. Compare with piezoelectric effect .
- **electrotinning**
  - Electroplating tin on an object.
- **electrotyping**
  - The production of printing plates by electroforming .
- **electrowinning**
  - Recovery of a metal from an ore by means of electrochemical processes.
- **elongation**
  - (1) A term used in mechanical testing to describe the amount of extension of a test piece when stressed. (2) In tensile testing, the increase in the gage length, measured after fracture of the specimen within the gage length, usually expressed as a percentage of the original gage length. See also elongation, percent .
- **elongation, percent**
  - The extension of a uniform section of a specimen expressed as a percentage of the original gage length:

$$\text{Elongation, \%} = \frac{(L_x - L_o)}{L_o} \times 100$$

  - where L_o is the original gage length and L_x is the final gage length.
- **elutriation**
  - A test for particle size in which the speed of a liquid or gas is used to suspend particles of a desired size, with larger sizes settling for removal and weighing, while smaller sizes are removed, collected, and weighed at certain time intervals.
- **embossing**
  - (1) Technique used to create depressions of a specific pattern in plastic film and sheeting. Such embossing in the form of surface patterns can be achieved on molded parts by the treatment of the mold surface with photoengraving or another process. (2) Raising a design in relief against a surface.
- **embossing die**
  - A die used for producing embossed designs.
- **embrittlement**
  - The severe loss of ductility or toughness or both, of a material, usually a metal or alloy. Many forms of embrittlement can lead to brittle fracture. Many forms can occur during thermal treatment or elevated-temperature service (thermally induced embrittlement). Some of these forms of embrittlement, which affect steels, include blue brittleness, 885 °F (475 °C) embrittlement, quench-age embrittlement, sigma-phase embrittlement, strain-age embrittlement, temper embrittlement, tempered martensite embrittlement, and thermal embrittlement. In addition, steels and other metals and alloys can be embrittled by environmental conditions (environmentally assisted embrittlement). The forms of environmental embrittlement include acid embrittlement, caustic embrittlement, corrosion embrittlement, creep-rupture embrittlement, hydrogen embrittlement, liquid metal embrittlement, neutron embrittlement, solder embrittlement, solid metal embrittlement, and stress-corrosion cracking.
- **emf**
  - An abbreviation for electromotive force .
- **emission spectroscopy**
  - The branch of spectroscopy treating the theory, interpretation, and application of spectra originating in the emission of electromagnetic radiation by atoms, ions, radicals, and molecules.

- **emissivity**
  - Ratio of the amount of energy or of energetic particles radiated from a unit area of a surface to the amount radiated from a unit area of an ideal emitter under the same conditions.
- **emulsion**
  - A stable dispersion of one liquid in another, generally by means of an emulsifying agent that has affinity for both the continuous and discontinuous phases. The emulsifying agent, discontinuous phase, and continuous phase can together produce another phase that serves as an enveloping (encapsulating) protective phase around the discontinuous phase.
- **emulsion cleaner**
  - A cleaner consisting of organic solvents dispersed in an aqueous medium with the aid of an emulsifying agent.
- **enameling iron**
  - A low-carbon, cold-rolled sheet steel, produced specifically for use as a base metal for porcelain enamel.
- **enantiotropy**
  - The relation of crystal forms of the same substance in which one form is stable above a certain temperature and the other form is stable below that temperature. For example, ferrite and austenite are enantiotropic in ferrous alloys.
- **end mark**
  - A roll mark caused by the end of a sheet marking the roll during hot or cold rolling.
- **end milling**
  - A method of machining with a rotating cutting tool with cutting edges on both the face end and the periphery. See also face milling and milling .
- **endothermic atmosphere**
  - A gas mixture produced by the partial combustion of a hydrocarbon gas with air in an endothermic reaction. Also known as endogas.
- **endothermic reaction**
  - Designating or pertaining to a reaction that involves the absorption of heat. See also exothermic reaction .
- **end-quench hardenability test**
  - A laboratory procedure for determining the hardenability of a steel or other ferrous alloy; widely referred to as the Jominy test. Hardenability is determined by heating a standard specimen above the upper critical temperature, placing the hot specimen in a fixture so that a stream of cold water impinges on one end, and, after cooling to room temperature is completed, measuring the hardness near the surface of the specimen at regularly spaced intervals along its length. The data are normally plotted as hardness versus distance from the quenched end.
- **endurance limit**
  - The maximum stress that a material can withstand for an infinitely large number of fatigue cycles. See also fatigue limit and fatigue strength .
- **endurance ratio**
  - The ratio of the endurance limit for completely reversed flexural stress to the tensile strength of a given material.
- **engineering strain (*e*)**
  - A term sometimes used for average linear strain or conventional strain in order to differentiate it from true strain. In tension testing it is calculated by dividing the change in the gage length by the original gage length.
- **engineering stress (*s*)**
  - A term sometimes used for conventional stress in order to differentiate it from true stress. In tension testing, it is calculated by dividing the breaking load applied to the specimen by the original cross-sectional area of the specimen.
- **environmental cracking**
  - Brittle fracture of a normally ductile material in which the corrosive effect of the environment is a causative factor. Environmental cracking is a general term that includes corrosion fatigue, high-temperature hydrogen attack, hydrogen blistering, hydrogen embrittlement, liquid metal embrittlement, solid metal embrittlement, stress-corrosion cracking, and sulfide stress cracking. The following terms have been used in the past in connection with environmental cracking, but are becoming obsolete: caustic embrittlement, delayed fracture, season cracking, static fatigue,

stepwise cracking, sulfide corrosion cracking, and sulfide stress-corrosion cracking. See also embrittlement .

- **epitaxy**
  - Growth of an electrodeposit or vapor deposit in which the orientation of the crystals in the deposit are directly related to crystal orientations in the underlying crystalline substrate.
- **epsilon (ε)**
  - Designation generally assigned to intermetallic, metal-metalloid, and metal-nonmetallic compounds found in ferrous alloy systems, for example, Fe_3Mo_2, FeSi, and Fe_3P.
- **epsilon carbide**
  - Carbide with hexagonal close-packed lattice that precipitates during the first stage of tempering of primary martensite. Its composition corresponds to the empirical formula $Fe_{2.4}C$.
- **epsilon structure**
  - Structurally analogous close-packed phases or electron compounds that have ratios of seven valence electrons to four atoms.
- **equiaxed grain structure**
  - A structure in which the grains have approximately the same dimensions in all directions.
- **equilibrium**
  - The dynamic condition of physical, chemical, mechanical, or atomic balance that appears to be a condition of rest rather than one of change.
- **equilibrium diagram**
  - A graph of the temperature, pressure, and composition limits of phase fields in an alloy system as they exist under conditions of thermodynamical equilibrium. In metal systems, pressure is usually considered constant. Compare with phase diagram .
- **Erichsen test**
  - A cupping test used to assess the ductility of sheet metal. The method consists of forcing a conical or hemispherical-ended plunger into the specimen and measuring the depth of the impression at fracture.
- **erosion**
  - (1) Loss of material from a solid surface due to relative motion in contact with a fluid that contains solid particles. Erosion in which the relative motion of particles is nearly parallel to the solid surface is called abrasive erosion. Erosion in which the relative motion of the solid particles is nearly normal to the solid surface is called impingement erosion or impact erosion. (2) Progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, and impinging liquid, or solid particles. (3) Loss of material from the surface of an electrical contact due to an electrical discharge (arcing). See also cavitation erosion , electrical pitting , and erosion-corrosion .
- **erosion-corrosion**
  - A conjoint action involving corrosion and erosion in the presence of a moving corrosive fluid, leading to the accelerated loss of material.
- **erosivity**
  - The characteristic of a collection of particles, liquid stream, or a slurry that expresses its tendency to cause erosive wear when forced against a solid surface under relative motion.
- **etchant**
  - A chemical solution used to etch a metal to reveal structural details. See also etching .
- **etch cleaning**
  - Removing soil by dissolving away some of the underlying metal.
- **etch cracks**
  - Shallow cracks in hardened steel containing high residual surface stresses, produced by etching in an embrittling acid.
- **etch figures**
  - Characteristic markings produced on crystal surfaces by chemical attack, usually having facets parallel to low-index crystallographic planes.
- **etching**
  - (1) Subjecting the surface of a metal to preferential chemical or electrolytic attack in order to reveal structural details for metallographic examination. (2) Chemically or electrochemically removing tenacious films from a metal surface to condition the surface for a subsequent treatment, such as painting or electroplating.
- **eutectic**

  - (1) An isothermal reversible reaction in which a liquid solution is converted into two or more intimately mixed solids on cooling, the number of solids formed being the same as the number of components in the system. (2) An alloy having the composition indicated by the eutectic point on a phase diagram. (3) An alloy structure of intermixed solid constituents formed by a eutectic reaction often in the form of regular arrays of lamellas or rods.
- **eutectic carbide**
  - Carbide formed during freezing as one of the mutually insoluble phases participating in the eutectic reaction of ferrous alloys.
- **eutectic melting**
  - Melting of localized microscopic areas whose composition corresponds to that of the eutectic in the system.
- **eutectic point**
  - The composition of a liquid phase in univariant equilibrium with two or more solid phases; the lowest melting alloy of a composition series.
- **eutectoid**
  - (1) An isothermal reversible reaction in which a solid solution is converted into two or more intimately mixed solids on cooling, the number of solids formed being the same as the number of components in the system. (2) An alloy having the composition indicated by the eutectoid point on a phase diagram. (3) An alloy structure of intermixed solid constituents formed by a eutectoid reaction.
- **eutectoid point**
  - The composition of a solid phase that undergoes univariant transformation into two or more other solid phases upon cooling.
- **exfoliation**
  - Corrosion that proceeds laterally from the sites of initiation along planes parallel to the surface, generally at grain boundaries, forming corrosion products that force metal away from the body of the material, giving rise to a layered appearance. Most commonly associated with wrought aluminum alloys.
- **exogenous inclusion**
  - An inclusion that is derived from external causes. Slag, dross, entrapped mold materials, and refractories are examples of inclusions that would be classified as exogenous. In most cases, these inclusions are macroscopic or visible to the naked eye. Compare with indigenous inclusion .
- **exothermic**
  - Characterized by the liberation of heat.
- **exothermic atmosphere**
  - A gas mixture produced by the partial combustion of a hydrocarbon gas with air in an exothermic reaction. Also known as exogas.
- **exothermic reaction**
  - A reaction that liberates heat, such as the burning of fuel or when certain plastic resins are cured chemically.
- **expanding**
  - A process used to increase the diameter of a cup, shell, or tube. See also bulging .
- **expendable pattern**
  - A pattern that is destroyed in making a casting. It is usually made of wax (investment casting) or expanded polystyrene (lost foam casting).
- **explosion welding**
  - A solid-state welding process that produces coalescence by a controlled detonation, which causes the parts to move together at high velocity. The resulting bond zone has a characteristic wavy appearance.
- **explosive forming**
  - The shaping of metal parts in which the forming pressure is generated by an explosive charge that takes the place of the punch in conventional forming. See also high-energy-rate forming .
- **extensometer**
  - An instrument for measuring changes in length over a given gage length caused by application or removal of a force. Commonly used in tension testing.
- **extractive metallurgy**

    - The branch of process metallurgy dealing with the winning of metals from their ores. Compare with refining .
- **extra hard**
    - A temper of nonferrous alloys and some ferrous alloys characterized by values of tensile strength and hardness about one-third of the way from those of full hard to those of extra spring temper.
- **extra spring**
    - A temper of nonferrous alloys and some ferrous alloys corresponding approximately to a cold-worked state above full hard beyond which further cold work will not measurably increase strength or hardness.
- **extreme-pressure lubricant**
    - A lubricant that imparts increased load-carrying capacity to rubbing surfaces under severe operating conditions. Extreme-pressure lubricants usually contain sulfur, halogens, or phosphorus.
- **extruded hole**
    - A hole formed by a punch that first cleanly cuts a hole and then is pushed farther through to form a flange with an enlargement of the original hole.
- **extrusion**
    - The conversion of an ingot or billet into lengths of uniform cross section by forcing metal to flow plastically through a die orifice. In forward (direct) extrusion, the die and ram are at opposite ends of the extrusion stock, and the product and ram travel in the same direction. Also, there is relative motion between the extrusion stock and the die. In backward (indirect) extrusion, the die is at the ram end of the stock and the product travels in the direction opposite that of the ram, either around the ram (as in the impact extrusion of cylinders such as cases for dry cell batteries) or up through the center of a hollow ram. See also hydrostatic extrusion and impact extrusion .
- **extrusion billet**
    - A metal slug used as extrusion stock .
- **extrusion defect**
    - See preferred term extrusion pipe .
- **extrusion forging**
    - (1) Forcing metal into or through a die opening by restricting flow in other directions. (2) A part made by the operation.
- **extrusion ingot**
    - A cast metal slug used as extrusion stock .
- **extrusion pipe**
    - A central oxide-lined discontinuity that occasionally occurs in the last 10 to 20% of an extruded metal bar. It is caused by the oxidized outer surface of the billet flowing around the end of the billet and into the center of the bar during the final stages of extrusion. Also called coring .
- **extrusion stock**
    - A rod, bar, or other section used to make extrusions.
- **eyeleting**
    - The displacing of material about an opening in sheet or plate so that a lip protruding above the surface is formed.
- **F**
- **face**
    - In a lathe tool, the surface against which the chips bear as they are formed.
- **face milling**
    - Milling a surface that is perpendicular to the cutter axis.
- **face-type cutters**
    - Cutters that can be mounted directly on and driven from the machine spindle nose.
- **facing**
    - (1) In machining, generating a surface on a rotating workpiece by the traverse of a tool perpendicular to the axis of rotation. (2) In foundry practice, any material applied in a wet or dry condition to the face of a mold or core to improve the surface of the casting. See also mold wash . (3) For abrasion resistance, see preferred term hardfacing .
- **failure**
    - A general term used to imply that a part in service (a) has become completely inoperable, (b) is still operable but incapable of satisfactorily performing its intended function, or (c) has deteriorated seriously, to the point that it has become unreliable or unsafe for continued use.

- **failure mechanism**
  - A structural or chemical process, such as corrosion or fatigue, that causes failure.
- **false bottom**
  - An insert put in either member of a die set to increase the strength and improve the life of the die.
- **false brinelling**
  - (1) Damage to a solid bearing surface characterized by indentations not caused by plastic deformation resulting from overload, but thought to be due to other causes such as fretting corrosion. (2) Local spots appearing when the protective film on a metal is broken continually by repeated impacts, usually in the presence of corrosive agents. The appearance is generally similar to that produced by brinelling but corrosion products are usually visible. It may result from fretting corrosion. This term should be avoided when a more precise description is possible. False brinelling (race fretting) can be distinguished from true brinelling because in false brinelling, surface material is removed so that original finishing marks are removed. The borders of a false brinell mark are sharply defined, whereas a dent caused by a rolling element does not have sharp edges and the finishing marks are visible in the bottom of the dent.
- **fatigue**
  - The phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the ultimate tensile strength of the material. Fatigue failure generally occurs at loads that applied statically would produce little perceptible effect. Fatigue fractures are progressive, beginning as minute cracks that grow under the action of the fluctuating stress.
- **fatigue crack growth rate (da/dN)**
  - The rate of crack extension caused by constant-amplitude fatigue loading, expressed in terms of crack extension per cycle of load application, and plotted logarithmically against the stress-intensity factor range, ΔK.
- **fatigue failure**
  - Failure that occurs when a specimen undergoing fatigue completely fractures into two parts or has softened or been otherwise significantly reduced in stiffness by thermal heating or cracking.
- **fatigue life (N)**
  - (1) The number of cycles of stress or strain of a specified character that a given specimen sustains before failure of a specified nature occurs. (2) The number of cycles of deformation required to bring about failure of a test specimen under a given set of oscillating conditions (stresses or strains). See also *S-N* curve .
- **fatigue limit**
  - The maximum stress that presumably leads to fatigue fracture in a specified number of stress cycles. The value of the maximum stress and the stress ratio also should be stated. See also endurance limit .
- **fatigue notch factor (K_f)**
  - The ratio of the fatigue strength of an unnotched specimen to the fatigue strength of a notched specimen of the same material and condition; both strengths are determined at the same number of stress cycles.
- **fatigue notch sensitivity (q)**
  - An estimate of the effect of a notch or hole of a given size and shape on the fatigue properties of a material, measured by $q = (K_f - 1)/(K_t - 1)$ where K_f is the fatigue notch factor and K_t is the stress-concentration factor. A material is said to be fully notch sensitive if q approaches a value of 1.0; it is not notch sensitive if the ratio approaches 0.
- **fatigue ratio**
  - The ratio of fatigue strength to tensile strength. Mean stress and alternating stress must be stated.
- **fatigue strength**
  - The maximum cyclical stress a material can withstand for a given number of cycles before failure occurs.
- **fatigue strength at N cycles (S_N)**
  - A hypothetical value of stress for failure at exactly N cycles as determined from an *S-N* curve. The value of S_N thus determined is subject to the same conditions as those that apply to the *S-N* curve. The value of S_N that is commonly found in the literature is the hypothetical value of maximum stress, S_{max}, minimum stress S_{min}, or stress amplitude, S_a, at which 50% of the specimens of a given sample could survive N stress cycles in which the mean stress $S_m = 0$. This is also known as the median fatigue strength at N cycles . See also *S-N* curve .
- **fatigue-strength reduction factor**

    - The ratio of the fatigue strength of a member or specimen with no stress concentration to the fatigue strength with stress concentration. This factor has no meaning unless the stress range and the shape, size, and material of the member or specimen are stated.
- **fatigue striation**
    - Parallel lines frequently observed in electron microscope fractographs or fatigue fracture surfaces. The lines are transverse to the direction of local crack propagation; the distance between successive lines represents the advance of the crack front during the one cycle of stress variation.
- **fatigue test**
    - A method for determining the range of alternating (fluctuating) stresses a material can withstand without failing.
- **fatigue wear**
    - (1) Removal of particles detached by fatigue arising from cyclic stress variations. (2) Wear of a solid surface caused by fracture arising from material fatigue. See also spalling .
- **faying surface**
    - The mating surface of a member that is in contact with or in close proximity to another member to which it is to be joined.
- **feed**
    - The rate at which a cutting tool or grinding wheel advances along or into the surface of a workpiece, the direction of advance depending on the type of operation involved.
- **feeder (feeder head, feedhead)**
    - In foundry practice, a riser .
- **feeding**
    - (1) In casting, providing molten metal to a region undergoing solidification, usually at a rate sufficient to fill the mold cavity ahead of the solidification front and to compensate for any shrinkage accompanying solidification. (2) Conveying metal stock or workpieces to a location for use or processing, such as wire to a consumable electrode, strip to a die, or workpieces to an assembler.
- **feed lines**
    - Linear marks on a machined or ground surface that are spaced at intervals equal to the feed per revolution or per stroke.
- **ferrimagnetic material**
    - (1) A material that macroscopically has properties similar to those of a ferromagnetic material but that microscopically also resembles an antiferromagnetic material in that some of the elementary magnetic moments are aligned antiparallel. If the moments are of different magnitudes, the material may still have a large resultant magnetization. (2) A material in which unequal magnetic moments are lined up antiparallel to each other. Permeabilities are of the same order of magnitude as those of ferromagnetic materials, but are lower than they would be if all atomic moments were parallel and in the same direction. Under ordinary conditions the magnetic characteristics of ferrimagnetic materials are quite similar to those of ferromagnetic material.
- **ferrite**
    - (1) A solid solution of one or more elements in body-centered cubic iron. Unless otherwise designated (for instance, as chromium ferrite), the solute is generally assumed to be carbon. On some equilibrium diagrams, there are two ferrite regions separated by an austenite area. The lower area is αferrite; the upper, δferrite. If there is no designation, αferrite is assumed. (2) An essentially carbon-free solid solution in which αiron is the solvent and which is characterized by a body-centered cubic crystal structure. Fully ferritic steels are only obtained when the carbon content is quite low. The most obvious microstructural features in such metals are the ferrite grain boundaries.
- **ferrite banding**
    - Parallel bands of free ferrite aligned in the direction of working. Sometimes referred to as ferrite streaks.
- **ferrite number**
    - An arbitrary, standardized value designating the ferrite content of an austenitic stainless steel weld metal. This value directly replaces percent ferrite or volume percent ferrite and is determined by the magnetic test described in AWS A4.2
- **ferrite-pearlite banding**
    - Inhomogeneous distribution of ferrite and pearlite aligned in filaments or plates parallel to the direction of working.

- **ferrite streaks**
  - Same as ferrite banding .
- **ferritic grain size**
  - The grain size of the ferritic matrix of a steel.
- **ferritic malleable**
  - See malleable iron .
- **ferritizing anneal**
  - A treatment given as-cast gray or ductile (nodular) iron to produce an essentially ferritic matrix. For the term to be meaningful, the final microstructure desired or the time-temperature cycle used must be specified.
- **ferroalloy**
  - An alloy of iron that contains a sufficient amount of one or more other chemical elements to be useful as an agent for introducing these elements into molten metal, especially into steel or cast iron.
- **ferroelectric**
  - A crystalline material that exhibits spontaneous electrical polarization, hysteresis, and piezoelectric properties.
- **ferroelectric effect**
  - The phenomenon whereby certain crystals may exhibit a spontaneous dipole moment (which is called ferroelectric by analogy with ferromagnetism exhibiting a permanent magnetic moment). Ferroelectric crystals often show several Curie points, domain structures, and hysteresis, much as do ferromagnetic crystals.
- **ferrograph**
  - An instrument used to determine the size distribution of wear particles in lubricating oils of mechanical systems. The technique relies on the debris being capable of being attracted to a magnet.
- **ferromagnetic material**
  - A material that in general exhibits the phenomena of hysteresis and saturation, and whose permeability is dependent on the magnetizing force. Microscopically, the elementary magnets are aligned parallel in volumes called domains (see domain, magnetic). The unmagnetized condition of a ferromagnetic material results from the overall neutralization of the magnetization of the domains to produce zero external magnetization.
- **ferromagnetism**
  - A property exhibited by certain metals, alloys, and compounds of the transition (iron group), rare-earth, and actinide elements in which, below a certain temperature termed the Curie temperature, the atomic magnetic moments tend to line up in a common direction. Ferromagnetism is characterized by the strong attraction of one magnetized body for another. See also Curie temperature . Compare with paramagnetism .
- **ferrous**
  - Metallic materials in which the principal component is iron.
- **fiber**
  - (1) The characteristic of wrought metal that indicates directional properties and is revealed by etching of a longitudinal section or is manifested by the fibrous or woody appearance of a fracture. It is caused chiefly by extension of the constituents of the metal, both metallic and nonmetallic, in the direction of working. (2) The pattern of preferred orientation of metal crystals after a given deformation process, usually wiredrawing. See also fibering and preferred orientation .
- **fibering**
  - Elongation and alignment of internal boundaries, second phases, and inclusions in particular directions corresponding to the direction of metal flow during deformation processing.
- **fiber metallurgy**
  - The technology of producing solid bodies from fibers or chopped filaments, with or without a metal matrix. The fibers may consist of such nonmetals as graphite or aluminum oxide, or of such metals as tungsten or boron. See also metal-matrix composites .
- **fiber stress**
  - Local stress through a small area (a point or line) on a section where the stress is not uniform, as in a beam under a bending load.
- **fibrous fracture**

  - A gray and amorphous fracture that results when a metal is sufficiently ductile for the crystals to elongate before fracture occurs. When a fibrous fracture is obtained in an impact test, it may be regarded as definite evidence of toughness of the metal. See also crystalline fracture and silky fracture .
- **fibrous structure**
  - (1) In forgings, a structure revealed as laminations, not necessarily detrimental, on an etched section or as a ropy appearance on a fracture. It is not to be confused with silky or ductile fracture of a clean metal. (2) In wrought iron, a structure consisting of slag fibers embedded in ferrite. (3) In rolled steel plate stock, a uniform, fine-grained structure on a fractured surface, free of laminations or shale-type discontinuities.
- **filamentary shrinkage**
  - A fine network of shrinkage cavities, occasionally found in steel castings, that produces a radiographic image resembling lace.
- **file hardness**
  - Hardness as determined by the use of a steel file of standardized hardness on the assumption that a material that cannot be cut with the file is as hard as, or harder than, the file. Files covering a range of hardnesses may be employed; the most common are files heat treated to approximately 67 to 70 HRC.
- **filiform corrosion**
  - Corrosion that occurs under some coatings in the form of randomly distributed thread-like filaments.
- **filler metal**
  - Metal added in making a brazed, soldered, or welded joint. See also brazing filler metal , electrode (welding) , solder , welding rod , and welding wire .
- **fillet**
  - (1) Concave corner piece usually used at the intersection of casting sections. Also the radius of metal at such junctions as opposed to an abrupt angular junction. (2) A radius (curvature) imparted to inside meeting surfaces.
- **final annealing**
  - An imprecise term used to denote the last anneal given to a nonferrous alloy prior to shipment.
- **final polishing**
  - A polishing process in which the primary objective is to produce a final surface suitable for microscopic examination.
- **fineness**
  - A measure of the purity of gold or silver expressed in parts per thousand.
- **fines**
  - (1) The product that passes through the finest screen in sorting crushed or ground material. (2) Sand grains that are substantially smaller than the predominating size in a batch or lot of foundry sand. (3) The portion of a powder composed of particles smaller than a specified size, usually 44 μm (325 mesh).
- **fine silver**
  - Silver with a fineness of three nines (999); equivalent to a minimum content of 99.9% Ag with the remaining content unrestricted.
- **finish**
  - (1) Surface condition, quality, or appearance of a metal. (2) Stock on a forging or casting to be removed in finish machining. (3) The forging operation in which the part is forged into its final shape in the finish die. If only one finish operation is scheduled to be performed in the finish die, this operation will be identified simply as finish; first, second, or third finish designations are so termed when one or more finish operations are to be performed in the same finish die.
- **finish allowance**
  - (1) The amount of excess metal surrounding the intended final configuration of a formed part; sometimes called forging envelope, machining allowance, or cleanup allowance. (2) Amount of stock left on the surface of a casting for machining.
- **finish annealing**
  - A subcritical annealing treatment applied to cold-worked low- or medium-carbon steel. Finish annealing, which is a compromise treatment, lowers residual stresses, thereby minimizing the risk of distortion in machining while retaining most of the benefits to machinability contributed by cold working. Compare with final annealing .

- **finished steel**
  - Steel that is ready for the market and has been processed beyond the stages of billets, blooms, sheet bars, slabs, and wire rods.
- **finisher (finishing impression)**
  - The die impression that imparts the final shape to a forged part.
- **finish grinding**
  - The final grinding action on a workpiece, of which the objectives are surface finish and dimensional accuracy.
- **finishing die**
  - The die set used in the last forging step.
- **finishing temperature**
  - The temperature at which hot working is completed.
- **finish machining**
  - A machining process analogous to finish grinding .
- **firecracker welding**
  - A variation of the shielded metal arc welding process in which a length of covered electrode is placed along the joint in contact with the workpieces. During the welding operation, the stationary electrode is consumed as the arc travels the length of the electrode.
- **fire-refined copper**
  - Copper that has been refined by the use of a furnace process only, including refinery shapes and, by extension, fabricators' products made therefrom. Usually, when this term is used alone it refers to fire-refined tough pitch copper without elements other than oxygen being present in significant amounts.
- **fir-tree crystal**
  - A type of dendrite .
- **fisheye**
  - An area on a steel fracture surface having a characteristic white crystalline appearance.
- **fisheye (weld defect)**
  - A discontinuity found on the fracture surface of a weld in steel that consists of a small pore or inclusion surrounded by an approximately round, bright area.
- **fishmouthing**
  - See alligatoring .
- **fishscale**
  - A scaly appearance in a porcelain enamel coating in which the evolution of hydrogen from the base metal (iron or steel) causes loss of adhesion between the enamel and the base metal. The scales are somewhat like blisters that have cracked partway around the perimeter but still remain attached to the coating around the rest of the perimeter.
- **fishtail**
  - (1) In roll forging, the excess trailing end of a forging. It is often used, before being trimmed off, as a tong hold for a subsequent forging operation. (2) In hot rolling or extrusion, the imperfectly shaped trailing end of a bar or special section that must be cut off and discarded as mill scrap.
- **fissure**
  - A small cracklike weld discontinuity with only slight separation (opening displacement) of the fracture surfaces. The prefixes macro or micro indicate relative size.
- **fixed-feed grinding**
  - Grinding in which the wheel is fed into the work, or vice versa, by given increments or at a given rate.
- **fixed position welding**
  - Welding in which the work is held in a stationary position.
- **fixture**
  - A device designed to hold parts to be joined in proper relation to each other.
- **flake**
  - A short, discontinuous internal crack in ferrous metals attributed to stresses produced by localized transformation and hydrogen-solubility effects during cooling after hot working. In fracture surfaces, flakes appear as bright, silvery areas with a coarse texture. In deep acid-etched transverse sections, they appear as discontinuities that are usually in the midway to center location of the section. Also termed hairline cracks and shatter cracks.
- **flake graphite**

    - Graphitic carbon, in the form of platelets, occurring in the microstructure of gray iron.
- **flaking**
    - (1) The removal of material from a surface in the form of flakes or scalelike particles. (2) A form of pitting resulting from fatigue. See also spalling .
- **flame annealing**
    - Annealing in which the heat is applied directly by a flame.
- **flame cleaning**
    - Cleaning metal surfaces of scale, rust, dirt, and moisture by use of a gas flame.
- **flame cutting**
    - See preferred term oxygen cutting .
- **flame hardening**
    - A process for hardening the surfaces of hardenable ferrous alloys in which an intense flame is used to heat the surface layers above the upper transformation temperature, whereupon the workpiece is immediately quenched.
- **flame spraying**
    - A thermal spraying process in which an oxyfuel gas flame is the source of heat for melting the surfacing material. Compressed gas may or may not be used for atomizing and propelling the surfacing material to the substrate.
- **flame straightening**
    - Correcting distortion in metal structures by localized heating with a gas flame.
- **flank**
    - The end surface of a tool that is adjacent to the cutting edge and below it when the tool is in a horizontal position, as for turning.
- **flank wear**
    - The loss of relief on the flank of the tool behind the cutting edge due to rubbing contact between the work and the tool during cutting; measured in terms of linear dimension behind the original cutting edge.
- **flare test**
    - A test applied to tubing, involving tapered expansion over a cone. Similar to pin expansion test .
- **flaring**
    - (1) Forming an outward acute-angle flange on a tubular part. (2) Forming a flange by using the head of a hydraulic press.
- **flash**
    - (1) In forging, metal in excess of that required to fill the blocking or finishing forging impression of a set of dies completely. Flash extends out from the body of the forging as a thin plate at the line where the dies meet and is subsequently removed by trimming. Because it cools faster than the body of the component during forging, flash can serve to restrict metal flow at the line where dies meet, thus ensuring complete filling of the impression. See also closed-die forging . (2) In casting, a fin of metal that results from leakage between mating mold surfaces. (3) In welding, the material that is expelled or squeezed out of a weld joint and that forms around the weld.
- **flashback**
    - A recession of the welding or cutting torch flame into or back of the mixing chamber of the torch.
- **flash extension**
    - That portion of flash remaining on a forged part after trimming; usually included in the normal forging tolerances.
- **flashing**
    - In flash welding, the heating portion of the cycle, consisting of a series of rapidly recurring localized short circuits followed by molten metal expulsions, during which time the surfaces to be welded are moved one toward the other at a predetermined speed.
- **flash land**
    - Configuration in the blocking or finishing impression of forging dies designed to restrict or to encourage the growth of flash at the parting line, whichever may be required in a particular case to ensure complete filling of the impression.
- **flash line**
    - The line left on a forging after the flash has been trimmed off.
- **flash plate**
    - A very thin final electrodeposited film of metal.
- **flash welding**

  - A resistance welding process that produces coalescence at the faying surfaces of abutting members by a flashing action and by the application of pressure after heating is substantially completed. The flashing action, caused by the very high current densities at small contacts between the parts, forcibly expels the material from the joint as the parts are slowly moved together. The weld is completed by a rapid upsetting of the workpieces.
- **flask**
  - A metal or wood frame used for making and holding a sand mold. The upper part is called the cope; the lower, the drag. See also blind riser .
- **flat-die forging**
  - Forging metal between flat or simple-contour dies by repeated strokes and manipulation of the workpiece. Also known as open-die forging , hand forging, or smith forging.
- **flat drill**
  - A rotary end-cutting tool constructed from a flat piece of material, provided with suitable cutting lips at the cutting end.
- **flat edge trimmer**
  - A machine for trimming notched edges on shells. The slide is cam driven so as to obtain a brief dwell at the bottom of the stroke, at which time the die, sometimes called a shimmy die, oscillates to trim the part.
- **flat-position welding**
  - Welding from the upper side, the face of the weld being horizontal. Also called downhand welding.
- **flattening**
  - (1) A preliminary operation performed on forging stock to position the metal for a subsequent forging operation. (2) The removal of irregularities or distortion in sheets or plates by a method such as roller leveling or stretcher leveling.
- **flattening dies**
  - Dies used to flatten sheet metal hems, that is, dies that can flatten a bend by closing it. These dies consist of a top and bottom die with a flat surface that can close one section (flange) to another (hem, seam).
- **flattening test**
  - A quality test for tubing in which a specimen is flattened to a specified height between parallel plates.
- **flat wire**
  - A roughly rectangular or square mill product, narrower than strip, in which all surfaces are rolled or drawn without any previous slitting, shearing, or sawing.
- **flaw**
  - A nonspecific term often used to imply a crack-like discontinuity. See preferred terms discontinuity and defect .
- **flexible cam**
  - An adjustable pressure-control cam of spring steel strips used to obtain varying pressure during a forming cycle.
- **flex roll**
  - A movable jump roll designed to push up against a metal sheet as it passes through a roller leveler. The flex roll can be adjusted to deflect the sheet any amount up to the roll diameter.
- **flex rolling**
  - Passing metal sheets through a flex roll unit to minimize yield-point elongation in order to reduce the tendency for stretcher strains to appear during forming.
- **flexural strength**
  - A property of solid material that indicates its ability to withstand a flexural or transverse load.
- **floating die**
  - (1) In metalforming, a die mounted in a die holder or punch mounted in its holder such that a slight amount of motion compensates for tolerance in the die parts, the work, or the press. (2) A die mounted on heavy springs to allow vertical motion in some trimming, shearing, and forming operations.
- **floating plug**
  - In tube drawing, an unsupported mandrel that locates itself at the die inside the tube, causing a reduction in wall thickness while the die is reducing the outside diameter of the tube.
- **flop forging**

  - A forging in which the top and bottom die impressions are identical, permitting the forging to be turned upside down during the forging operation.
- **flospinning**
  - Forming cylindrical, conical and curvilinear shaped parts by power spinning over a rotating mandrel. See also spinning .
- **flotation**
  - The concentration of valuable minerals from ores by agitation of the ground material with water, oil, and flotation chemicals. The valuable minerals are generally wetted by the oil, lifted to the surface by clinging air bubbles, and then floated off.
- **flow**
  - Movement (slipping or sliding) of essentially parallel planes within an element of a material in parallel directions; occurs under the action of shear stress. Continuous action in this manner, at constant volume and without disintegration of the material, is termed yield, creep, or plastic deformation.
- **flowability**
  - (1) In casting, a characteristic of a foundry sand mixture that enables it to move under pressure or vibration so that it makes intimate contact with all surfaces of the pattern or core box. (2) In welding, brazing, or soldering, the ability of molten filler metal to flow or spread over a metal surface.
- **flow brightening**
  - (1) Melting of an electrodeposit, followed by solidification, especially of tin plate. (2) Fusion (melting) of a chemically or mechanically deposited metallic coating on a substrate, particularly as it pertains to soldering.
- **flow lines**
  - (1) Texture showing the direction of metal flow during hot or cold working. Flow lines can often be revealed by etching the surface or a section of a metal part. See accompanying macrograph. (2) In mechanical metallurgy, paths followed by minute volumes of metal during deformation.
- **flow stress**
  - The stress required to produce plastic deformation in a solid metal.
- **flow through**
  - A forging defect caused by metal flow past the base of a rib with resulting rupture of the grain structure.
- **fluid-cell process**
  - A modification of the Guerin process for forming sheet metal, the fluid-cell process uses higher pressure and is primarily designed for forming slightly deeper parts, using a rubber pad as either the die or punch. A flexible hydraulic fluid cell forces an auxiliary rubber pad to follow the contour of the form block and exert a nearly uniform pressure at all points on the workpiece. See also fluid forming and rubber-pad forming .
- **fluid forming**
  - A modification of the Guerin process , fluid forming differs from the fluid-cell process in that the die cavity, called a pressure dome, is not completely filled with rubber, but with hydraulic fluid retained by cup-shaped rubber diaphragm. See also rubber-pad forming .
- **fluidity**
  - The ability of liquid metal to run into and fill a mold cavity.
- **fluidized bed**
  - A contained mass of a finely divided solid that behaves like a fluid when brought into suspension in a moving gas or liquid.
- **fluorescent magnetic-particle inspection**
  - Inspection with either dry magnetic particles or those in a liquid suspension, the particles being coated with a fluorescent substance to increase the visibility of the indications.
- **fluorescent penetrant inspection**
  - Inspection using a fluorescent liquid that will penetrate any surface opening; after the surface has been wiped clean, the location of any surface flaws may be detected by the fluorescence, under ultraviolet light, of back-seepage of the fluid.
- **fluoroscopy**
  - An inspection procedure in which the radiographic image of the subject is viewed on a fluorescent screen, normally limited to low-density materials or thin sections of metals because of the low light output of the fluorescent screen at safe levels of radiation.

- **flute**
  - (1) As applied to drills, reamers, and taps, the channels or grooves formed in the body of the tool to provide cutting edges and to permit passage of cutting fluid and chips. (2) As applied to milling cutters and hobs, the chip space between the back of one tooth and the face of the following tooth.
- **flutes**
  - Elongated grooves or voids that connect widely spaced cleavage planes.
- **fluting**
  - (1) Forming longitudinal recesses in a cylindrical part, or radial recesses in a conical part. (2) A series of sharp parallel kinks or creases occurring in the arc when sheet metal is roll formed into a cylindrical shape. (3) Grinding the grooves of a twist drill or tap.
- **flux**
  - (1) In metal refining, a material added to a melt to remove undesirable substances, like sand, ash, or dirt. Fluxing of the melt facilitates the agglomeration and separation of such undesirable constituents from the melt. It is also used as a protective covering for certain molten metal baths. Lime or limestone is generally used to remove sand, as in iron smelting; sand, to remove iron oxide in copper refining. (2) In brazing, cutting, soldering, or welding, material used to prevent the formation of, or to dissolve and facilitate removal of, oxides and other undesirable substances.
- **flux cored arc welding (FCAW)**
  - An arc welding process that joins metal by heating them with an arc between a continuous tubular filler-metal electrode and the work. Shielding is provided by a flux contained within the consumable tubular electrode. Additional shielding may or may not be obtained from an externally supplied gas or gas mixture. See also flux cored electrode .
- **flux cored electrode**
  - A composite filler metal electrode consisting of a metal tube or other hollow configuration containing ingredients to provide such functions as shielding atmosphere, deoxidation, arc stabilization, and slag formation. Minor amounts of alloying materials may be included in the core. External shielding may or may not be used.
- **flux density**
  - In magnetism, the number of flux lines per unit area passing through a cross section at right angles. It is given by $B = \mu H$, where μ and H are permeability and magnetic-field intensity, respectively.
- **flux lines**
  - Imaginary lines used as a means of explaining the behavior of magnetic and other fields. Their concept is based on the pattern of lines produced when magnetic particles are sprinkled over a permanent magnet. Sometimes called magnetic lines of force.
- **fly cutting**
  - Cutting with a single-tooth milling cutter.
- **flying shear**
  - A machine for cutting continuous rolled products to length that does not require a halt in rolling, but rather moves along the runout table at the same speed as the product while performing the cutting, and then returns to the starting point in time to cut the next piece.
- **fog quenching**
  - Quenching in a fine vapor or mist.
- **foil**
  - Metal in sheet form less than 0.15 mm (0.006 in.) thick.
- **fold**
  - (1) A defect in metal, usually on or near the surface, caused by continued fabrication of overlapping surfaces. (2) A forging defect caused by folding metal back onto its own surface during its flow in the die cavity. See also lap .
- **follow board**
  - In foundry practice, a board contoured to a pattern to facilitate the making of a sand mold.
- **follow die**
  - A progressive die consisting of two or more parts in a single holder; used with a separate lower die to perform more than one operation (such as piercing and blanking) on a part in two or more stations.
- **forced-air quench**

  - A quench utilizing blasts of compressed air against relatively small parts such as a gear.
- **forgeability**
  - Term used to describe the relative ability of material to deform without fracture. Also describes the resistance to flow from deformation. See also formability .
- **forged roll Scleroscope hardness number (HFRSc or HFRSd)**
  - A number related to the height of rebound of a diamond-tipped hammer dropped on a forged steel roll. It is measured on a scale determined by dividing into 100 units the average rebound of a hammer from a forged steel roll of accepted maximum hardness. See also Scleroscope hardness number and Scleroscope hardness test .
- **forged structure**
  - The macrostructure through a suitable section of a forging that reveals direction of working.
- **forge welding**
  - Solid-state welding in which metals are heated in a forge (in air) and then welded together by applying pressure or blows sufficient to cause permanent deformation at the interface.
- **forging**
  - The process of working metal to a desired shape by impact or pressure in hammers, forging machines (upsetters), presses, rolls, and related forming equipment. Forging hammers, counterblow equipment, and high-energy-rate forging machines apply impact to the workpiece, while most other types of forging equipment apply squeeze pressure in shaping the stock. Some metals can be forged at room temperature, but most are made more plastic for forging by heating. Specific forging processes defined in this glossary include closed-die forging , high-energy-rate forging , hot upset forging , isothermal forging , open-die forging , powder forging , precision forging , radial forging , ring rolling , roll forging , rotary forging , and rotary swaging .
- **forging billet**
  - A wrought metal slug used as forging stock .
- **forging dies**
  - Forms for making forgings; they generally consist of a top and bottom die. The simplest will form a completed forging in a single impression; the most complex, consisting of several die inserts, may have a number of impressions for the progressive working of complicated shapes. Forging dies are usually in pairs, with part of the impression in one of the blocks and the rest of the impression in the other block.
- **forging envelope**
  - See finish allowance .
- **forging ingot**
  - A cast metal slug used as forging stock .
- **forging machine (upsetter or header).**
  - A type of forging equipment, related to the mechanical press , in which the principal forming energy is applied horizontally to the workpiece, which is gripped and held by prior action of the dies. See also heading , hot upset forging , and upsetting .
- **forging plane**
  - In forging, the plane that includes the principal die face and that is perpendicular to the direction of ram travel. When parting surfaces of the dies are flat, the forging plane coincides with the parting line.
- **forging range**
  - Temperature range in which a metal can be forged successfully.
- **forging rolls**
  - Power-driven rolls used in preforming bar or billet stock that have shaped contours and notches for introduction of the work. See also roll forging .
- **forging stock**
  - A wrought rod, bar, or other section suitable for subsequent change in cross section by forging.
- **formability**
  - The ease with which a metal can be shaped through plastic deformation. Evaluation of the formability of a metal involves measurement of strength, ductility, and the amount of deformation required to cause fracture. The term workability is used interchangeably with formability; however, formability refers to the shaping of sheet metal, while workability refers to shaping materials by bulk forming. See also forgeability .
- **form block**

  - Tooling, usually the male part, used for forming sheet metal contours; generally used in rubber-pad forming.
- **form cutter**
  - Any cutter, profile sharpened or cam relieved, shaped to produce a specified form on the work.
- **form die**
  - A die used to change the shape of a sheet metal blank with minimal plastic flow.
- **form grinding**
  - Grinding with a wheel having a contour on its cutting face that is a mating fit to the desired form.
- **forming**
  - (1) Making a change, with the exception of shearing or blanking, in the shape or contour of a metal part without intentionally altering its thickness. (2) The plastic deformation of a billet or a blanked sheet between tools (dies) to obtain the final configuration. Metalforming processes are typically classified as bulk forming and sheet forming. Also referred to as metalworking.
- **forming limit diagram (FLD)**
  - A diagram in which the major strains at the onset of necking in sheet metal are plotted vertically and the corresponding minor strains are plotted horizontally. The onset-of-failure line divides all possible strain combinations into two zones: the safe zone (in which failure during forming is not expected) and the failure zone (in which failure during forming is expected).
- **form-relieved cutter**
  - A cutter so relieved that by grinding only the tooth face of the original form is maintained throughout its life.
- **form rolling**
  - Hot rolling to produce bars having contoured cross sections; not to be confused with roll forming of sheet metal or with roll forging.
- **form tool**
  - A single-edge, nonrotating cutting tool, circular or flat, that produces its inverse or reverse form counterpart upon a workpiece.
- **forward extrusion**
  - Same as direct extrusion. See extrusion .
- **fouling**
  - An accumulation of deposits. This term includes accumulation and growth of marine organisms on a submerged metal surface and also includes the accumulation of deposits (usually inorganic) on heat exchanger tubing. See also biological corrosion .
- **foundry**
  - A commercial establishment or building where metal castings are produced.
- **foundry returns**
  - Metal in the form of gates, sprues, runners, risers, and scrapped castings of known composition returned to the furnace for remelting.
- **four-high mill**
  - A type of rolling mill, commonly used for flat-rolled mill products, in which two large-diameter backup rolls are employed to reinforce two smaller work rolls, which are in contact with the product. Either the work rolls or the backup rolls may be driven. Compare with two-high mill and cluster mill .
- **four-point press**
  - A press whose slide is actuated by four connections and four cranks, eccentrics, or cylinders, the chief merit being to equalize the pressure at the corners of the slides.
- **fractography**
  - Descriptive treatment of fracture of materials, with specific reference to photographs of the fracture surface. Macrofractography involves photographs at low magnification (<25×); microfractography, photographs at high magnification (>25×).
- **fracture**
  - The irregular surface produced when a piece of metal is broken. See also brittle fracture , cleavage fracture , crystalline fracture , decohesive rupture , dimple rupture , ductile fracture , fibrous fracture , granular fracture , intergranular fracture , silky fracture , and transgranular fracture .
- **fracture grain size**

  - Grain size determined by comparing a fracture of a specimen with a set of standard fractures. For steel, a fully martensitic specimen is generally used, and the depth of hardening and the prior austenitic grain size are determined.
- **fracture mechanics**
  - A quantitative analysis for evaluating structural behavior in terms of applied stress, crack length, and specimen or machine component geometry. See also linear elastic fracture mechanics .
- **fracture strength**
  - The normal stress at the beginning of fracture. Calculated from the load at the beginning of fracture during a tension test and the original cross-sectional area of the specimen.
- **fracture stress**
  - The true, normal stress on the minimum cross-sectional area at the beginning of fracture. The term usually applies to tension tests of unnotched specimens.
- **fracture surface markings**
  - Fracture surface features that may be used to determine the fracture origin location and the nature of the stress that produced the fracture.
- **fracture test**
  - Test in which a specimen is broken and its fracture surface is examined with the unaided eye or with a low-power microscope to determine such factors as composition, grain size, case depth, or discontinuities.
- **fracture toughness**
  - A generic term for measures of resistance to extension of a crack. The term is sometimes restricted to results of fracture mechanics tests, which are directly applicable in fracture control. However, the term commonly includes results from simple tests of notched or precracked specimens not based on fracture mechanics analysis. Results from tests of the latter type are often useful for fracture control, based on either service experience or empirical correlations with fracture mechanics tests. See also stress-intensity factor .
- **fragmentation**
  - The subdivision of a grain into small, discrete crystallite outlined by a heavily deformed network of intersecting slip bands as a result of cold working. These small crystals or fragments differ in orientation and tend to rotate to a stable orientation determined by the slip systems.
- **freckling**
  - A type of segregation revealed as dark spots on a macroetched specimen of a consumable-electrode vacuum-arc-remelted alloy.
- **free bend**
  - The bend obtained by applying forces to the ends of a specimen without the application of force at the point of maximum bending.
- **free carbon**
  - The part of the total carbon in steel or cast iron that is present in elemental form as graphite or temper carbon. Contrast with combined carbon .
- **free ferrite**
  - (1) Ferrite that is formed directly from the decomposition of hypoeutectoid austenite during cooling, without the simultaneous formation of cementite. (2) Ferrite formed into separate grains and not intimately associated with carbides as in pearlite. Also called *proeutectoid ferrite.*
- **free machining**
  - Pertains to the machining characteristics of an alloy to which one or more ingredients have been introduced to produce small broken chips, lower power consumption, better surface finish, and longer tool life; among such additions are sulfur or lead to steel, lead to brass, lead and bismuth to aluminum, and sulfur or selenium to stainless steel.
- **freezing point**
  - See preferred term liquidus and solidus . See also melting point .
- **freezing range**
  - That temperature range between liquidus and solidus temperatures in which molten and solid constituents coexist.
- **fretting**
  - A type of wear that occurs between tight-fitting surfaces subjected to cyclic relative motion of extremely small amplitude. Usually, fretting is accompanied by corrosion, especially of the very fine wear debris. Also referred to as fretting corrosion and false brinelling (in rolling-element bearings).

- **fretting corrosion**
  - (1) The accelerated deterioration at the interface between contacting surfaces as the result of corrosion and slight oscillatory movement between the two surfaces. (2) A form of fretting in which chemical reaction predominates. Fretting corrosion is often characterized by the removal of particles and subsequent formation of oxides, which are often abrasive and so increase the wear. Fretting corrosion can involve other chemical reaction products, which may not be abrasive.
- **fretting fatigue**
  - (1) Fatigue fracture that initiates at a surface area where fretting has occurred. The progressive damage to a solid surface that arises from fretting. *Note:* If particles of wear debris are produced, then the term fretting wear may be applied.
- **fretting wear**
  - Wear arising as a result of fretting .
- **friction**
  - The resisting force tangential to the common boundary between two bodies when, under the action of an external force, one body moves or tends to move relative to the surface of the other.
- **friction coefficient**
  - See coefficient of friction .
- **friction welding (FRW)**
  - A solid-state welding process that produces coalescence of materials under compressive force contact of workpieces rotating or moving relative to one another to produce heat and plastically displace material from the faying surfaces.
- **fuel gases**
  - Gases usually used with oxygen for heating such as acetylene, natural gas, hydrogen, propane, stabilized methylacetylene propadiene, and other synthetic fuels and hydrocarbons.
- **full annealing**
  - An imprecise term that denotes an annealing cycle to produce minimum strength and hardness. For the term to be meaningful, the composition and starting condition of the material and the time-temperature cycle used must be stated.
- **full center**
  - Mild waviness down the center of a metal sheet or strip.
- **fuller (fullering impression)**
  - Portion of the die used in hammer forging primarily to reduce the cross section and to lengthen a portion of the forging stock. The fullering impression is often used in conjunction with an edger (edging impression) .
- **full hard**
  - A temper of nonferrous alloys and some ferrous alloys corresponding approximately to a cold-worked state beyond which the material can no longer be formed by bending. In specifications, a full hard temper is commonly defined in terms of minimum hardness or minimum tensile strength (or, alternatively, a range of hardness or strength) corresponding to a specific percentage of cold reduction following a full anneal. For aluminum, a full hard temper is equivalent to a reduction of 75% from dead soft ; for austenitic stainless steels, a reduction of about 50 to 55%.
- **full mold**
  - A trade name for an expendable pattern casting process in which the polystyrene pattern is vaporized by the molten metal as the mold is poured. See also lost foam casting .
- **furnace brazing**
  - A mass-production brazing process in which the filler metal is preplaced on the joint, then the entire assembly is heated to brazing temperature in a furnace.
- **fused spray deposit**
  - A self-fluxing spray deposit which is deposited by conventional thermal spraying and subsequently fused using either a heating torch or a furnace.
- **fused zone**
  - See preferred terms fusion zone , nugget , and weld interface .
- **fusible alloys**
  - A group of binary, ternary, quaternary, and quinary alloys containing bismuth, lead, tin, cadmium, and indium. The term "fusible alloy" refers to any of more than 100 alloys that melt at relatively low temperatures, that is, below the melting point of tin-lead solder (183 °C, or 360 °F). The melting points of these alloys range as low as 47 °C (116 °F).

- **fusion**
  - The melting together of filler metal and base metal (substrate), or of base metal only, which results in coalescence. See also depth of fusion .
- **fusion welding**
  - Any welding process that uses fusion of the base metal to make the weld.
- **fusion zone**
  - The area of base metal melted as determined on the cross section of a weld.
- **G**
- **gage**
  - (1) The thickness of sheet or the diameter of wire. The various standards are arbitrary and differ with regard to ferrous and nonferrous products as well as sheet and wire. (2) An aid for visual inspection that enables an inspector to determine more reliably whether the size or contour of a formed part meets dimensional requirements. (3) An instrument used to measure thickness or length.
- **gage length**
  - The original length of that portion of the specimen over which strain, change of length and other characteristics are measured.
- **gall**
  - To damage the surface of a powder metallurgy compact or die part, caused by adhesion of powder to the die cavity wall or a punch surface.
- **galling**
  - (1) A condition whereby excessive friction between high spots results in localized welding with subsequent spalling and a further roughening of the rubbing surfaces of one or both of two mating parts. (2) A severe form of scuffing associated with gross damage to the surfaces or failure. Galling has been used in many ways in tribology; therefore, each time it is encountered its meaning must be ascertained from the specific context of the usage. See also scoring and scuffing .
- **galvanic cell**
  - (1) A cell in which chemical change is the source of electrical energy. It usually consists of two dissimilar conductors in contact with each other and with an electrolyte, or of two similar conductors in contact with each other and with dissimilar electrolytes. (2) A cell or system in which a spontaneous oxidation-reduction reaction occurs, the resulting flow of electrons being conducted in an external part of the circuit.
- **galvanic corrosion**
  - Corrosion associated with the current of a galvanic cell consisting of two dissimilar conductors in an electrolyte or two similar conductors in dissimilar electrolytes. Where the two dissimilar metals are in contact, the resulting reaction is referred to as couple action.
- **galvanic couple**
  - A pair of dissimilar conductors, commonly metals, in electrical contact. See also galvanic corrosion .
- **galvanic current**
  - The electric current that flows between metals or conductive nonmetals in a galvanic couple.
- **galvanic series**
  - A list of metals and alloys arranged according to their relative corrosion potentials in a given environment. Compare with electromotive force series .
- **galvanize**
  - To coat a metal surface with zinc using any of various processes.
- **galvanneal**
  - To produce a zinc-iron alloy coating on iron or steel by keeping the coating molten after hot dip galvanizing until the zinc alloys completely with the basis metal.
- **gamma iron**
  - The face-centered cubic form of pure iron, stable from 910 to 1400 °C (1670 to 2550 °F).
- **gamma ray**
  - Short-wavelength electromagnetic radiation, similar to x-rays but of nuclear origin, with a range of wavelength from about 10^{-14} to 10^{-10} m. See also electromagnetic radiation .
- **gamma structure**
  - Structurally analogous phases or electron compounds having ratios of 21 valence electrons to 13 atoms. This is generally a large, complex cubic structure.

- **gang milling**
  - Milling with several cutters mounted on the same arbor or with workpieces similarly positioned for cutting either simultaneously or consecutively during a single setup.
- **gang slitter**
  - A machine with a number of pairs of rotary cutters spaced on two parallel shafts, used for slitting metal into strips or for trimming the edges of sheets.
- **gangue**
  - The worthless portion of an ore that is separated from the desired part before smelting is commenced.
- **gap-frame press**
  - A general classification of press in which the uprights or housings are made in the form of a letter C, thus making three sides of the die space accessible.
- **gas atomization**
  - An atomization process whereby molten metal is broken up into particles by a rapidly moving inert gas stream.
- **gas classification**
  - The separation of a powder into its particle size fractions by means of a gas stream of controlled velocity flowing counterstream to the gravity-induced fall of the particles. The method is used to classify submesh-size particles.
- **gaseous corrosion**
  - Corrosion with gas as the only corrosive agent and without any aqueous phase on the surface of the metal. Also called dry corrosion. See also hot corrosion , oxidation , and sulfidation .
- **gas holes**
  - Holes in castings or welds that are formed by gas escaping from molten metal as it solidifies. Gas holes may occur individually, in clusters, or throughout the solidified metal.
- **gas metal arc cutting**
  - An arc cutting process used to sever metals by melting them with the heat of an arc between a continuous metal (consumable) electrode and the work. Shielding is obtained entirely from an externally supplied gas or gas mixture.
- **gas metal arc welding (GMAW)**
  - An arc welding process that produces coalescence of metals by heating them with an arc between a continuous filler metal electrode and the workpieces. Shielding is obtained entirely from an externally supplied gas.
- **gas pocket**
  - A cavity caused by entrapped gas.
- **gas porosity**
  - Fine holes or pores within a metal that are caused by entrapped gas or by the evolution of dissolved gas during solidification.
- **gas shielded arc welding**
  - A general term used to describe gas metal arc welding, gas tungsten arc welding, and flux cored arc welding (when gas shielding is employed).
- **gassing**
  - (1) Absorption of gas by a metal. (2) Evolution of gas from a metal during melting operations or upon solidification. (3) Evolution of gas from an electrode during electrolysis.
- **gas torch**
  - See preferred terms cutting torch (arc) , cutting torch (oxyfuel gas) , welding torch (arc) , and welding torch (oxyfuel gas) .
- **gas tungsten arc cutting**
  - An arc-cutting process in which metals are severed by melting them with an arc between a single tungsten (nonconsumable) electrode and the workpiece. Shielding is obtained from a gas or gas mixture.
- **gas tungsten arc welding (GTAW)**
  - An arc welding process that produces coalescence of metals by heating them with an arc between a tungsten (nonconsumable) electrode and the work. Shielding is obtained from a gas or gas mixture. Pressure may or may not be used and filler metal may or may not be used.
- **gas welding**
  - See preferred term oxyfuel gas welding .
- **gate**

  - The portion of the runner in a mold through which molten metal enters the mold cavity. The generic term is sometimes applied to the entire network of connecting channels that conduct metal into the mold cavity. See also gating system .
- **gated pattern**
  - In foundry practice, a pattern that includes not only the contours of the part to be cast but also the gates.
- **gathering**
  - A forging operation that increases the cross section of part of the stock; usually a preliminary operation.
- **gathering stock**
  - Any operation whereby the cross section of a portion of the forging stock is increased beyond its original size.
- **gating system**
  - The complete assembly of sprues, runners, and gates in a mold through which metal flows to enter casting cavity. The term is also applied to equivalent portions of the pattern.
- **gear cutting**
  - Producing tooth profiles of equal spacing on the periphery, internal surface, or face of a workpiece by means of an alternate shear gear-form cutter or a gear generator.
- **geared press**
  - A press whose main crank or eccentric shaft is connected by gears to the driving source.
- **gear hobbing**
  - Gear cutting by use of a tool resembling a worm gear in appearance, having helically spaced cutting teeth. In a single-thread hob, the rows of teeth advance exactly one pitch as the hob makes one revolution. With only one hob, it is possible to cut interchangeable gears of a given pitch of any number of teeth within the range of the hobbing machine.
- **gear milling**
  - Gear cutting with a milling cutter that has been formed to the shape of the tooth space to be cut. The tooth spaces are machined one at a time.
- **gear shaping**
  - Gear cutting with a reciprocating gear-shaped cutter rotating in mesh with the work blank.
- **general corrosion**
  - (1) A form of deterioration that is distributed more or less uniformly over a surface. (2) Corrosion dominated by uniform thinning that proceeds without appreciable localized attack. See also uniform corrosion .
- **gibs**
  - Guides or shoes that ensure the proper parallelism, squareness, and sliding fit between metalforming press components such as the slide and the frame. They are usually adjustable to compensate for wear and to establish operating clearance.
- **glazing**
  - Dulling the abrasive grains in the cutting face of a wheel during grinding.
- **glide**
  - (1) Same as slip . (2) A noncrystallographic shearing movement, such as of one grain over another.
- **globular transfer**
  - In consumable-electrode arc welding, a type of metal transfer in which molten filler metal passes across the arc as large droplets. Compare with short-circuiting transfer and spray transfer .
- **gold filled**
  - Covered on one or more surfaces with a layer of gold alloy to form a clad or composite material. Gold-filled dental restorations are an example of such materials.
- **gooseneck**
  - In die casting, a spout connecting a molten metal holding pot, or chamber, with a nozzle or sprue hole in the die and containing a passage through which molten metal is forced on its way to the die. It is the metal injection mechanism in a hot chamber machine .
- **gouging**
  - In welding practice, the forming of a bevel or groove by material removal. See also arc gouging and oxygen gouging .
- **gouging abrasion**

  - A form of high-stress abrasion in which easily observable grooves or gouges are created on the surface. See also abrasion .
- **G-P zone**
  - A Guinier-Preston zone .
- **graded abrasive**
  - An abrasive powder in which the sizes of the individual particles are confined to certain specified limits. See also grit size .
- **grain**
  - An individual crystal in a polycrystalline material; it may or may not contain twinned regions and subgrains.
- **grain boundary**
  - A narrow zone in a metal or ceramic corresponding to the transition from one crystallographic orientation to another, thus separating one grain from another; the atoms in each grain are arranged in an orderly pattern.
- **grain-boundary corrosion**
  - Same as intergranular corrosion . See also interdendritic corrosion .
- **grain-boundary sulfide precipitation**
  - An intermediate state of overheating of metals in which sulfide inclusions are redistributed to the austenitic grain boundaries by partial solution at the overheating temperature and reprecipitation during subsequent cooling.
- **grain coarsening**
  - A heat treatment that produces excessively large austenitic grains in metals.
- **grain flow**
  - Fiberlike lines on polished and etched sections of forgings caused by orientation of the constituents of the metal in the direction of working during forging. Grain flow produced by proper die design can improve required mechanical properties of forgings. See also flow lines and forged structure .
- **grain growth**
  - (1) An increase in the average size of the grains in polycrystalline material, usually as a result of heating at elevated temperature. (2) In polycrystalline materials, a phenomenon occurring fairly close below the melting point in which the larger grains grow still larger while the smallest ones gradually diminish and disappear. See also recrystallization .
- **grain refinement**
  - The manipulation of the solidification process to cause more (and therefore smaller) grains to be formed and/or to cause the grains to form in specific shapes. The term refinement is usually used to denote a chemical addition to the metal but can refer to control of the cooling rate.
- **grain refiner**
  - A material added to a molten metal to induce a finer-than-normal grain size in the final structure.
- **grain size**
  - (1) For metals, a measure of the areas or volumes of grains in a polycrystalline material, usually expressed as an average when the individual sizes are fairly uniform. In metals containing two or more phases, grain size refers to that of the matrix unless otherwise specified. Grain size is reported in terms of number of grains per unit area or volume, in terms of average diameter, or as a grain-size number derived from area measurements. (2) For grinding wheels, see preferred term grit size .
- **grain size distribution**
  - Measures of the characteristic grain or crystallite dimensions (usually, diameters) in a polycrystalline solid; or of their populations by size increments from minimum to maximum. Usually determined by microscopy.
- **granular fracture**
  - A type of irregular surface produced when metal is broken that is characterized by a rough, grainlike appearance, rather than a smooth or fibrous one. It can be subclassified as transgranular fracture or intergranular fracture. This type of fracture is frequently called crystalline fracture; however, the inference that the metal broke because it "crystallized" is not justified, because all metals are crystalline in the solid state. See also fibrous fracture and silky fracture .
- **granulated metal**
  - Small pellets produced by pouring liquid metal through a screen or by dropping it onto a revolving disk, and, in both instances, chilling with water.

- **graphitic carbon**
  - Free carbon in steel or cast iron.
- **graphitic corrosion**
  - Corrosion of gray iron in which the iron matrix is selectively leached away, leaving a porous mass of graphite behind; it occurs in relatively mild aqueous solutions and on buried pipe and fittings.
- **graphitic steel**
  - Alloy steel made so that part of the carbon is present as graphite.
- **graphitization**
  - The formation of graphite in iron or steel. Where graphite is formed during solidification, the phenomenon is termed primary graphitization; where formed later by heat treatment, secondary graphitization.
- **graphitizing**
  - Annealing a ferrous alloy such that some or all the carbon precipitates as graphite.
- **gravity hammer**
  - A class of forging hammer in which energy for forging is obtained by the mass and velocity of a freely falling ram and the attached upper die. Examples are the board hammer and air-lift hammer.
- **gravity segregation**
  - Variable composition of a casting or ingot caused by settling out of heavy constituents, or rising of light constituents, before or during solidification.
- **gray cast iron**
  - See gray iron .
- **gray iron**
  - A cast iron characterized by a gray fracture surface due to the presence of flake graphite.
- **green compact**
  - An unsintered powder metallurgy or ceramic compact.
- **green density**
  - The density of a green compact .
- **green rot**
  - A form of high-temperature attack on stainless steels, nickel-chromium alloys, and nickel-chromium-iron alloys subjected to simultaneous oxidation and carburization. Basically, attack occurs first by precipitation of chromium as chromium carbide, then by oxidation of the carbide particles.
- **green sand**
  - A naturally bonded sand, or a compounded molding sand mixture, that has been "tempered" with water and that is used while still moist.
- **green sand core**
  - (1) A core made of green sand and used as-rammed. (2) A sand core that is used in the unbaked condition.
- **green sand mold**
  - A casting mold composed of moist prepared molding sand. Contrast with dry sand mold .
- **green strength**
  - (1) The strength of a tempered foundry sand mixture at room temperature. (2) The ability of a green compact to maintain its size and shape during handling and storage prior to sintering. (3) The tensile or compressive strength of a green compact.
- **grindability**
  - Relative ease of grinding, analogous to machinability .
- **grindability index**
  - A measure of the grindability of a material under specified grinding conditions, expressed in terms of volume of material removed per unit volume of wheel wear.
- **grinding**
  - Removing material from a workpiece with a grinding wheel or abrasive belt.
- **grinding burn**
  - See burning .
- **grinding cracks**

  - Shallow cracks formed in the surfaces of relatively hard materials because of excessive grinding heat or the high sensitivity of the material. See also grinding sensitivity .
- **grinding fluid**
  - An oil- or water-based fluid introduced into grinding operations to (1) reduce and transfer heat during grinding, (2) lubricate during chip formation, (3) wash loose chips or swarf from the grinding belt or wheel, and (4) chemically aid the grinding action or machine maintenance.
- **grinding oil**
  - An oil-type grinding fluid; it may contain additives, but not water.
- **grinding relief**
  - A groove or recess located at the boundary of a surface to permit the corner of the wheel to overhang during grinding.
- **grinding sensitivity**
  - Susceptibility of a material to surface damage such as grinding cracks; it can be affected by such factors as hardness, microstructure, hydrogen content, and residual stress.
- **grinding stress**
  - Residual stress, generated by grinding, in the surface layer of work. It may be tensile or compressive, or both.
- **grinding wheel**
  - A cutting tool of circular shape made of abrasive grains bonded together. See also diamond wheels .
- **grit**
  - Crushed ferrous or synthetic abrasive material in various mesh sizes that is used in abrasive blasting equipment to clean castings. For materials used for grinding belts or grinding wheels, see the preferred term abrasive .
- **grit blasting**
  - Abrasive blasting with small irregular pieces of steel, malleable cast iron, or hard nonmetallic materials.
- **grit size**
  - Nominal size of abrasive particles in a grinding wheel, corresponding to the number of openings per linear inch in a screen through which the particles can pass.
- **Grossmann number (*H*)**
  - A ratio describing the ability of a quenching medium to extract heat from a hot steel workpiece in comparison to still water defined by the following equation:

$$H = \frac{h}{2k}$$

  - where h is the heat transfer coefficient and k is the conductivity of the metal.
- **gross porosity**
  - In weld metal or in a casting, pores, gas holes, or globular voids that are larger and in much greater numbers than those obtained in good practice.
- **groundbed**
  - A buried item, such as junk steel or graphite rods, that serves as the anode for the cathodic protection of pipelines or other buried structures.
- **ground connection**
  - In arc welding, a device used for attaching the work lead (ground cable) to the work.
- **growth (cast iron)**
  - A permanent increase in the dimensions of cast iron resulting from repeated or prolonged heating at temperatures above 480 °C (900 °F) due either to graphitizing of carbides or oxidation.
- **Guerin process**
  - A rubber-pad forming process for forming sheet metal. The principal tools are the rubber pad and form block, or punch.
- **guided bend**
  - The bend obtained by use of a plunger to force the specimen into a die in order to produce the desired contour of the outside and inside surfaces of the specimen.
- **guided bend test**

  - A test in which the specimen is bent to a definite shape by means of a punch (mandrel) and a bottom block.
- **guide mill**
  - A small hand mill with several stands in a train and with guides for the work at the entrance to the rolls.
- **Guinier-Preston (G-P) zone**
  - A small precipitation domain in a supersaturated metallic solid solution. A G-P zone has no well-defined crystalline structure of its own and contains an abnormally high concentration of solute atoms. The formation of G-P zones constitutes the first stage of precipitation and is usually accompanied by a change in properties of the solid solution in which they occur.
- **gun drill**
  - A drill, usually with one or more flutes and with coolant passages through the drill body, used for deep hole drilling.
- **gutter**
  - A depression around the periphery of a forging die impression outside the flash pan that allows space for the excess metal; surrounds the finishing impression and provides room for the excess metal used to ensure a sound forging. A shallow impression outside the parting line.
- **H**
- **habit plane**
  - The plane or system of planes of a crystalline phase along which some phenomenon, such as twinning or transformation, occurs.
- **Hadfield steel**
  - See austenitic manganese steel .
- **half cell**
  - An electrode immersed in a suitable electrolyte, designed for measurements of electrode potential.
- **half hard**
  - A temper of nonferrous alloys and some ferrous alloys characterized by tensile strength about midway between those of dead soft and full hard tempers.
- **Hall process**
  - A commercial process for winning aluminum from alumina by electrolytic reduction of a fused bath of alumina dissolved in cryolite.
- **hammer**
  - A machine that applies a sharp blow to the work area through the fall of a ram onto an anvil. The ram can be driven by gravity or power. See also gravity hammer .
- **hammer forging**
  - Forging in which the work is deformed by repeated blows.
- **hammering**
  - The working of metal sheet into a desired shape over a form or on a high-speed hammer and a similar anvil to produce the required dishing or thinning.
- **hammer welding**
  - Forge welding by hammering.
- **hand brake**
  - A small manual folding machine designed to bend sheet metal, similar in design and purpose to a press brake .
- **hand forge (smith forge)**
  - A forging operation in which forming is accomplished on dies that are generally flat. The piece is shaped roughly to the required contour with little or no lateral confinement; operations involving mandrels are included. The term hand forge refers to the operation performed, while hand forging applies to the part produced.
- **handling breaks**
  - Irregular breaks caused by improper handling of metal sheets during processing. These breaks result from bending or sagging of the sheets during handling.
- **hard chromium**
  - Chromium electrodeposited for engineering purposes (such as to increase the wear resistance of sliding metal surfaces) rather than as a decorative coating. It is usually applied directly to substrate and is customarily thicker (>1.2 μm, or 0.05 mil) than a decorative deposit, but not necessarily harder.

- **hard drawn**
  - An imprecise term applied to drawn products, such as wire and tubing, that indicates substantial cold reduction without subsequent annealing. Compare with light drawn .
- **hardenability**
  - The relative ability of a ferrous alloy to form martensite when quenched from a temperature above the upper critical temperature. Hardenability is commonly measured as the distance below a quenched surface at which the metal exhibits a specific hardness (50 HRC, for example) or a specific percentage of martensite in the microstructure.
- **hardener**
  - An alloy rich in one or more alloying elements that is added to a melt to permit closer control of composition than is possible by the addition of pure metals, or to introduce refractory elements not readily alloyed with the base metal. Sometimes called master alloy or rich alloy.
- **hardening**
  - Increasing hardness of metals by suitable treatment, usually involving heating and cooling. When applicable, the following, more specific terms should be used: age hardening , case hardening , flame hardening , induction hardening , precipitation hardening , and quench hardening .
- **hardfacing**
  - The application of a hard, wear-resistant material to the surface of a component by welding, spraying, or allied welding processes to reduce wear or loss of material by abrasion, impact, erosion, galling, and cavitation. See also surfacing .
- **hardfacing alloys**
  - Wear-resistant materials available as bare welding rod, flux-coated rod, long-length solid wires, long-length tubular wires, or powders that are deposited by hardfacing.
- **hard metal**
  - A collective term that designates a sintered material with high hardness, strength, and wear resistance and is characterized by a tough metallic binder phase and particles of carbides, borides, or nitrides of the refractory metals. The term is in general use abroad, while for the carbides the term cemented carbide is preferred in the U.S., and the boride and nitride materials are usually categorized as cermets .
- **hardness**
  - A measure of the resistance of a material to surface indentation or abrasion; may be thought of as a function of the stress required to produce some specified type of surface deformation. There is no absolute scale for hardness; therefore, to express hardness quantitatively, each type of test has its own scale of arbitrarily defined hardness. Indentation hardness can be measured by Brinell, Rockwell, Vickers, Knoop, and Scleroscope hardness tests.
- **hard solder**
  - A term erroneously used to denote silver-base brazing filler metals.
- **hard surfacing**
  - See preferred terms surfacing or hardfacing .
- **hard temper**
  - Same as full hard temper.
- **Haring cell**
  - A four-electrode cell for measurement of electrolyte resistance and electrode polarization during electrolysis.
- **H-band steel**
  - Carbon, carbon-boron, or alloy steel produced to specified limits of hardenability; the chemical composition range may be slightly different from that of the corresponding grade of ordinary carbon or alloy steel.
- **heading**
  - The upsetting of wire, rod, or bar stock in dies to form parts that usually contain portions that are greater in cross-sectional area than the original wire, rod, or bar.
- **hearth**
  - The bottom portions of certain furnaces, such as blast furnaces, air furnaces, and other reverberatory furnaces, that support the charge and sometimes collect and hold molten metal.
- **heat**
  - A stated tonnage of metal obtained from a period of continuous melting in a cupola or furnace, or the melting period required to handle this tonnage.
- **heat-affected zone (HAZ)**

    - That portion of the base metal that was not melted during brazing, cutting, or welding, but whose microstructure and mechanical properties were altered by the heat.
- **heat check**
    - A pattern of parallel surface cracks that are formed by alternate rapid heating and cooling of the extreme surface metal, sometimes found on forging dies and piercing punches. There may be two sets of parallel cracks, one set perpendicular to the other.
- **heat-resistant alloy**
    - An alloy developed for very-high-temperature service where relatively high stresses (tensile, thermal, vibratory, or shock) are encountered and where oxidation resistance is frequently required.
- **heat sink**
    - A material that absorbs or transfers heat away from a critical element or part.
- **heat tinting**
    - Coloration of a metal surface through oxidation by heating to reveal details of the microstructure.
- **heat treatable alloy**
    - An alloy that can be hardened by heat treatment.
- **heat treating film**
    - A thin coating or film, usually an oxide, formed on the surface of a metal during heat treatment.
- **heat treatment**
    - Heating and cooling a solid metal or alloy in such a way as to obtain desired conditions or properties. Heating for the sole purpose of hot working is excluded from the meaning of this definition.
- **heavy metal**
    - A sintered tungsten alloy with nickel, copper, and/or iron, the tungsten content being at least 90 wt% and the density being at least 16.8 g/cm^3.
- **heel**
    - Synonymous with base .
- **heel block**
    - A block or plate usually mounted on or attached to a lower die in a forming or forging press that serves to prevent or minimize the deflection of punches or cams.
- **hemming**
    - A bend of 180° made in two steps. First, a sharp-angle bend is made; next the bend is closed using a flat punch and a die.
- **HERF**
    - A common abbreviation for high-energy-rate forging or high-energy-rate forming .
- **herringbone pattern**
    - Same as chevron pattern .
- **high-conductivity copper**
    - Copper that, in the annealed condition, has a minimum electrical conductivity of 100% IACS as determined by ASTM test methods.
- **high-cycle fatigue**
    - Fatigue that occurs at relatively large numbers of cycles. The arbitrary, but commonly accepted, dividing line between high-cycle fatigue and low-cycle fatigue is considered to be about 10^4 to 10^5 cycles. In practice, this distinction is made by determining whether the dominant component of the strain imposed during cyclic loading is elastic (high cycle) or plastic (low cycle), which in turn depends on the properties of the metal and on the magnitude of the nominal stress.
- **high-energy-rate forging (HERF)**
    - A closed-die hot- or cold-forging process in which the stored energy of high-pressure gas is used to accelerate a ram to unusually high velocities in order to effect deformation of the workpiece. Ideally, the final configuration of the forging is developed in one blow or, at most, a few blows. In high-energy-rate forging, the velocity of the ram, rather than its mass, generates the major forging force. Also known as HERF processing, high-velocity forging, and high-speed forging.
- **high-energy-rate forming**
    - A group of forming processes that applies a high rate of strain to the material being formed through the application of high rates of energy transfer. See also explosive forming , high-energy-rate forging , and electromagnetic forming .
- **high frequency resistance welding**

  - A group of resistance welding process variations that uses high frequency welding current to concentrate the welding heat at the desired location.
- **highlighting**
  - Buffing or polishing selected areas of a complex shape to increase the luster or change the color of those areas.
- **high residual phosphorus copper**
  - Deoxidized copper with residual phosphorus present in amounts (usually 0.013 to 0.04%) generally sufficient to decrease appreciably the conductivity of the copper.
- **high-speed machining**
  - High-productivity machining processes that achieve cutting speeds in excess of 600 m/min (2000 sfm) and up to 18,000 m/min (60,000 sfm).
- **high-strength low-alloy (HSLA) steels**
  - Steels designed to provide better mechanical properties and/or greater resistance to atmospheric corrosion than conventional carbon steels. They are not considered to be alloy steels in the normal sense because they are designed to meet specific mechanical properties rather than a chemical composition (HSLA steels have yield strengths greater than 275 MPa, or 40 ksi). The chemical composition of a specific HSLA steel may vary for different product thicknesses to meet mechanical property requirements. The HSLA steels have low carbon contents (0.05 to 0.25% C) in order to produce adequate formability and weldability, and they have manganese contents up to 2.0%. Small quantities of chromium, nickel, molybdenum, copper, nitrogen, vanadium, niobium, titanium, and zirconium are used in various combinations.
- **high-temperature hydrogen attack**
  - A loss of strength and ductility of steel by high-temperature reaction of absorbed hydrogen with carbides in the steel resulting in decarburization and internal fissuring.
- **hindered contraction**
  - Contraction where the shape will not permit a metal casting to contract in certain regions in keeping with the coefficient of expansion.
- **HIP**
  - See hot isostatic pressing .
- **hob**
  - A rotary cutting tool with its teeth arranged along a helical thread, used for generating gear teeth or other evenly spaced forms on the periphery of a cylindrical workpiece. The hob and the workpiece are rotated in timed relationship to each other while the hob is fed axially or tangentially across or radially into the workpiece. Hobs should not be confused with multiple-thread milling cutters, rack cutters, and similar tools, where the teeth are not arranged along a helical thread.
- **hogging**
  - Machining a part from bar stock, plate, or a simple forging in which much of the original stock is removed.
- **holddown plate (pressure pad)**
  - A pressurized plate designed to hold the workpiece down during a press operation. In practice, this plate often serves as a stripper and is also called a stripper plate.
- **holding**
  - In heat treating of metals, that portion of the thermal cycle during which the temperature of the object is maintained constant.
- **holding furnace**
  - A furnace into which molten metal can be transferred to be held at the proper temperature until it can be used to make castings.
- **holding temperature**
  - In heat treating of metals, the constant temperature at which the object is maintained.
- **holding time**
  - Time for which the temperature of the heat treated metal object is maintained constant.
- **hole expansion test**
  - A simulative test in which a flat metal sheet specimen with a circular hole in its center is clamped between annular die plates and deformed by a punch, which expands and ultimately cracks the edge of the hole.
- **hole flanging**

  - The forming of an integral collar around the periphery of a previously formed hole in a sheet metal part.
- **holidays**
  - Discontinuities in a coating (such as porosity, cracks, gaps, and similar flaws) that allow areas of substrate to be exposed to any corrosive environment that contacts the coated surface.
- **homogeneous carburizing**
  - Use of a carburizing process to convert a low-carbon ferrous alloy to one of uniform and higher carbon content throughout the section.
- **homogenizing**
  - A heat treating practice whereby a metal object is held at high temperature to eliminate or decrease chemical segregation by diffusion.
- **honing**
  - A low-speed finishing process used chiefly to produce uniform high dimensional accuracy and fine finish, most often on inside cylindrical surfaces. In honing, very thin layers of stock are removed by simultaneously rotating and reciprocating a bonded abrasive stone or stick that is pressed against the surface being honed with lighter force than is typical of grinding.
- **Hooke's law**
  - A generalization applicable to all solid material, which states that stress is directly proportional to strain and is expressed as:

$$\frac{\text{Stress}}{\text{Strain}} = \frac{\sigma}{\varepsilon} = \text{constant} = E$$

  - where *E* is the modulus of elasticity or Young's modulus. The constant relationship between stress and strain applies only below the proportional limit. See also modulus of elasticity .
- **Hoopes process**
  - An electrolytic refining process for aluminum, using three liquid layers in the reduction cell.
- **horn**
  - (1) In a resistance welding machine, a cylindrical arm or beam that transmits the electrode pressure and usually conducts the welding current. (2) A cone-shaped member that transmits ultrasonic energy from a transducer to a welding or machining tool. See also ultrasonic impact grinding and ultrasonic welding .
- **horn press**
  - A mechanical metal forming press equipped with or arranged for a cantilever block or horn that acts as the die or support for the die, used in forming, piercing, setting down, or riveting hollow cylinders and odd-shaped work.
- **horn spacing**
  - The distance between adjacent surfaces of the horns of a resistance welding machine.
- **hot box process**
  - In foundry practice, resin-base (furan or phenolic) binder process for molding sands similar to shell coremaking; cores produced with it are solid unless mandrelled out.
- **hot chamber machine**
  - A die casting machine in which the metal chamber under pressure is immersed in the molten metal in a furnace. The chamber is sometimes called a gooseneck, and the machine is sometimes called a gooseneck machine.
- **hot-cold working**
  - (1) A high-temperature thermomechanical treatment consisting of deforming a metal above its transformation temperature and cooling fast enough to preserve some or all of the deformed structure. (2) A general term synonymous with warm working .
- **hot corrosion**
  - An accelerated corrosion of metal surfaces that results from the combined effect of oxidation and reactions with sulfur compounds and other contaminants, such as chlorides, to form a molten salt on a metal surface that fluxes, destroys, or disrupts the normal protective oxide. See also gaseous corrosion .
- **hot crack**
  - A crack that develops in a weldment or casting during solidification.
- **hot-die forging**

  - A hot forging process in which both the dies and the forging stock are heated; typical die temperatures are 110 to 225 °C (200 to 400 °F) lower than the temperature of the stock. Compare with isothermal forging .
- **hot dip**
  - Covering a surface by dipping the surface to be coated into a molten bath of the coating material. See also hot dip coating .
- **hot dip coating**
  - A metallic coating obtained by dipping the substrate into a molten metal.
- **hot extrusion**
  - A process whereby a heated billet is forced to flow through a shaped die opening. The temperature at which extrusion is performed depends on the material being extruded. Hot extrusion is used to produce long, straight metal products of constant cross section, such as bars, solid and hollow sections, tubes, wires, and strips, from materials that cannot be formed by cold extrusion.
- **hot forging**
  - (1) A forging process in which the die and/or forging stock are heated. See also hot-die forging and isothermal forging . (2) The plastic deformation of a pressed and/or sintered powder compact in at least two directions at temperatures above the recrystallization temperature.
- **hot forming**
  - See hot working .
- **hot isostatic pressing**
  - (1) A process for simultaneously heating and forming a compact in which the powder is contained in a sealed flexible sheet metal or glass enclosure and the so-contained powder is subjected to equal pressure from all directions at a temperature high enough to permit plastic deformation and sintering to take place. (2) A process that subjects a component (casting, powder forgings, etc.) to both elevated temperature and isostatic gas pressure in an autoclave. The most widely used pressurizing gas is argon. When castings are hot isostatically pressed, the simultaneous application of heat and pressure virtually eliminates internal voids and microporosity through a combination of plastic deformation, creep, and diffusion.
- **hot mill**
  - A production line or facility for hot rolling of metals.
- **hot press forging**
  - Plastically deforming metals between dies in presses at temperatures high enough to avoid strain hardening.
- **hot pressing**
  - Simultaneous heating and forming of a powder compact. See also pressure sintering .
- **hot pressure welding**
  - A solid-state welding process that produces coalescence of materials with heat and application of pressure sufficient to produce macrodeformation of the base material. Vacuum or other shielding media may be used. See also diffusion welding and forge welding . Compare with cold welding .
- **hot quenching**
  - An imprecise term for various quenching procedures in which a quenching medium is maintained at a prescribed temperature above 70 °C (160 °F).
- **hot shortness**
  - A tendency for some alloys to separate along grain boundaries when stressed or deformed at temperatures near the melting point. Hot shortness is caused by a low-melting constituent, often present only in minute amounts, that is segregated at grain boundaries.
- **hot tear**
  - A fracture formed in a metal during solidification because of hindered contraction .
- **hot top**
  - (1) A reservoir, thermally insulated or heated, that holds molten metal on top of a mold for feeding of the ingot or casting as it contracts on solidifying, thus preventing formation of pipe or voids. (2) A refractory-lined steel or iron casting that is inserted into the tip of the mold and is supported at various heights to feed the ingot as it solidifies.
- **hot trimming**
  - The removal of flash or excess metal from a hot part (such as a forging) in a trimming press.
- **hot upset forging**

  - A bulk forming process for enlarging and reshaping some of the cross-sectional area of a bar, tube, or other product form of uniform (usually round) section. It is accomplished by holding the heated forging stock between grooved dies and applying pressure to the end of the stock, in the direction of its axis, by the use of a heading tool, which spreads (upsets) the end by metal displacement. Also called hot heading or hot upsetting. See also heading and upsetting .
- **hot-worked structure**
  - The structure of a material worked at a temperature higher than the recrystallization temperature.
- **hot working**
  - (1) The plastic deformation of metal at such a temperature and strain rate that recrystallization takes place simultaneously with the deformation, thus avoiding any strain hardening. Also referred to as hot forging and hot forming. (2) Controlled mechanical operations for shaping a product at temperatures above the recrystallization temperature. Contrast with cold working .
- **hubbing**
  - The production of forging die cavities by pressing a male master plug, known as a hub, into a block of metal.
- **Hull cell**
  - A special electrodeposition cell giving a range of known current densities for test work.
- **hydraulic hammer**
  - A gravity-drop forging hammer that uses hydraulic pressure to lift the hammer between strokes.
- **hydraulic-mechanical press brake**
  - A mechanical press brake that uses hydraulic cylinders attached to mechanical linkages to power the ram through its working stroke.
- **hydraulic press**
  - A press in which fluid pressure is used to actuate and control the ram. Hydraulic presses are used for both open- and closed-die forging.
- **hydrodynamic machining**
  - Removal of material by the impingement of a high-velocity fluid against a workpiece. See also waterjet/abrasive waterjet machining .
- **hydrogen-assisted cracking (HAC)**
  - See hydrogen embrittlement .
- **hydrogen-assisted stress-corrosion cracking (HSCC)**
  - See hydrogen embrittlement .
- **hydrogen blistering**
  - The formation of blisters on or below a metal surface from excessive internal hydrogen pressure. Hydrogen may be formed during cleaning, plating, or corrosion.
- **hydrogen brazing**
  - A term sometimes used to denote brazing in a hydrogen-containing atmosphere, usually in a furnace; use of the appropriate process name is preferred.
- **hydrogen damage**
  - A general term for the embrittlement, cracking, blistering, and hydride formation that can occur when hydrogen is present in some metals.
- **hydrogen embrittlement**
  - A process resulting in a decrease of the toughness or ductility of a metal due to the presence of atomic hydrogen. Hydrogen embrittlement has been recognized classically as being of two types. The first, known as internal hydrogen embrittlement, occurs when the hydrogen enters molten metal which becomes supersaturated with hydrogen immediately after solidification. The second type, environmental hydrogen embrittlement, results from hydrogen being absorbed by solid metals. This can occur during elevated-temperature thermal treatments and in service during electroplating, contact with maintenance chemicals, corrosion reactions, cathodic protection, and operating in high-pressure hydrogen. In the absence of residual stress or external loading, environmental hydrogen embrittlement is manifested in various forms, such as blistering, internal cracking, hydride formation, and reduced ductility. With a tensile stress or stress-intensity factor exceeding a specific threshold, the atomic hydrogen interacts with the metal to induce subcritical crack growth leading to fracture. In the absence of a corrosion reaction (polarized cathodically), the usual term used is hydrogen-assisted cracking (HAC) or hydrogen stress cracking (HSC). In the presence of active corrosion, usually as pits or crevices (polarized anodically), the cracking is generally called stress-corrosion cracking (SCC), but should more properly be called hydrogen-assisted stress-corrosion cracking (HSCC). Thus, HSC and electrochemically anodic SCC can

operate separately or in combination (HSCC). In some metals, such as high-strength steels, the mechanism is believed to be all, or nearly all, HSC. The participating mechanism of HSC is not always recognized and may be evaluated under the generic heading of SCC.

- **hydrogen-induced cracking (HIC)**
  - Same as hydrogen embrittlement .
- **hydrogen-induced delayed cracking**
  - A term sometimes used to identify a form of hydrogen embrittlement in which a metal appears to fracture spontaneously under a steady stress less than the yield stress. There is usually a delay between the application of stress (or exposure of the stressed metal to hydrogen) and the onset of cracking. Also referred to as static fatigue.
- **hydrogen loss**
  - The loss in weight of metal powder or a compact caused by heating a representative sample according to a specified procedure in a purified hydrogen atmosphere. Broadly, a measure of the oxygen content of the sample when applied to materials containing only such oxides as are reducible with hydrogen and no hydride-forming element.
- **hydrogen overvoltage**
  - In electroplating, overvoltage associated with the liberation of hydrogen gas.
- **hydrogen stress cracking (HSC)**
  - See hydrogen embrittlement .
- **hydrometallurgy**
  - Industrial winning or refining of metals using water or an aqueous solution.
- **hydrostatic extrusion**
  - A method of extruding a billet through a die by pressurized fluid instead of the ram used in conventional extrusion.
- **hydrostatic pressing**
  - A special case of isostatic pressing that uses a liquid such as water or oil as a pressure transducing medium and is therefore limited to near room-temperature operation.
- **hydrostatic tension**
  - Three equal and mutually perpendicular tensile stresses.
- **hypereutectic alloy**
  - In an alloy system exhibiting a eutectic, any alloy whose composition has an excess of alloying element compared with the eutectic composition and whose equilibrium microstructure contains some eutectic structure.
- **hypereutectoid alloy**
  - In an alloy system exhibiting a eutectoid, any alloy whose composition has an excess of alloying element compared with the eutectoid composition, and whose equilibrium microstructure contains some eutectoid structure.
- **hypoeutectic alloy**
  - In an alloy system exhibiting a eutectic, any alloy whose composition has an excess of base metal compared with the eutectic composition and whose equilibrium microstructure contains some eutectic structure.
- **hypoeutectoid alloy**
  - In an alloy system exhibiting a eutectoid, any alloy whose composition has an excess of base metal compared with the eutectoid composition and whose equilibrium microstructure contains some eutectoid structure.
- **hysteresis (magnetic)**
  - The lag of the magnetization of a substance behind any cyclic variation of the applied magnetizing field.
- **hysteresis (mechanical)**
  - The phenomenon of permanently absorbed or lost energy that occurs during any cycle of loading or unloading when a material is subjected to repeated loading.
- **I**
- **IACS**
  - International annealed copper standard; a standard reference used in reporting electrical conductivity. The conductivity of a material, in %IACS, is equal to 1724.1 divided by the electrical resistivity of the material in n$\Omega \cdot$ m.
- **ideal critical diameter (D_I)**

  - Under an ideal quench condition, the bar diameter that has 50% martensite at the center of the bar when the surface is cooled at an infinitely rapid rate (that is, when $H = \infty$, where H is the quench severity factor or Grossmann number).
- **idiomorphic crystal**
  - An individual crystal that has grown without restraint so that the habit planes are clearly developed. Compare with allotriomorphic crystal .
- **immersed-electrode furnace**
  - A furnace used for liquid carburizing of parts by heating molten salt baths with the use of electrodes immersed in the liquid. See also submerged-electrode furnace .
- **immersion cleaning**
  - Cleaning in which the work is immersed in a liquid solution.
- **immersion coating**
  - A coating produced in a solution by chemical or electrochemical action without the use of external current.
- **immersion plating**
  - Depositing a metallic coating on a metal immersed in a liquid solution, without the aid of an external electric current. Also called dip plating.
- **impact energy**
  - The amount of energy, usually given in joules or foot-pound force, required to fracture a material, usually measured by means of an Izod test or Charpy test. The type of specimen and test conditions affect the values and therefore should be specified.
- **impact extrusion**
  - The process (or resultant product) in which a punch strikes a slug (usually unheated) in a confining die. The metal flow may be either between punch and die or through another opening. The impact extrusion of unheated slugs is often called cold extrusion.
- **impact line**
  - A blemish on a drawn sheet metal part caused by a slight change in metal thickness. The mark is called an impact line when it results from the impact of the punch on the blank; it is called a recoil line when it results from transfer of the blank from the die to the punch during forming, or from a reaction to the blank being pulled sharply through the draw ring.
- **impact load**
  - An especially severe shock load such as that caused by instantaneous arrest of a falling mass, by shock meeting of two parts (in a mechanical hammer, for example), or by explosive impact, in which there can be an exceptionally rapid buildup of stress.
- **impact strength**
  - A measure of the resiliency or toughness of a solid. The maximum force or energy of a blow (given by a fixed procedure) that can be withstood without fracture, as opposed to fracture strength under a steady applied force.
- **impact test**
  - A test for determining the energy absorbed in fracturing a test piece at high velocity, as distinct from static test. The test may be carried out in tension, bending, or torsion, and the test bar may be notched or unnotched. See also Charpy test , impact energy , and Izod test .
- **impact wear**
  - Wear of a solid surface resulting from repeated collisions between that surface and another solid body. The term erosion is preferred in the case of multiple impacts and when the impacting body or bodies are very small relative to the surface being impacted.
- **impingement**
  - A process resulting in a continuing succession of impacts between liquid or solid particles and a solid surface.
- **impingement attack**
  - Corrosion associated with turbulent flow of liquid. May be accelerated by entrained gas bubbles. See also erosion-corrosion and impingement corrosion .
- **impingement corrosion**
  - A form of erosion-corrosion generally associated with the local impingement of a high-velocity, flowing fluid against a solid surface.
- **impingement erosion**
  - Loss of material from a solid surface due to liquid impingement. See also erosion .
- **impregnation**

    - (1) Treatment of porous castings with a sealing medium to stop pressure leaks. (2) The process of filling the pores of a sintered compact, usually with a liquid such as a lubricant. (3) The process of mixing particles of a nonmetallic substance in a cemented carbide matrix, as in diamond-impregnated tools.
- **impression-die forging**
    - A forging that is formed to the required shape and size by machined impressions in specially prepared dies that exert three-dimensional control on the workpiece.
- **impurities**
    - (1) Elements or compounds whose presence in a material is undesirable. (2) In a chemical or material, minor constituent(s) or component(s) not included deliberately; usually to some degree or above some level, undesirable.
- **inclinable press**
    - A press that can be inclined to facilitate handling of the formed parts. See also open-back inclinable press .
- **inclusion**
    - (1) A physical and mechanical discontinuity occurring within a material or part, usually consisting of solid, encapsulated foreign material. Inclusions are often capable of transmitting some structural stresses and energy fields, but to a noticeably different degree than from the parent material. (2) Particles of foreign material in a metallic matrix. The particles are usually compounds, such as oxides, sulfides, or silicates, but may be of any substance that is foreign to (and essentially insoluble in) the matrix. See also exogenous inclusion , indigenous inclusion , and stringer .
- **inclusion count**
    - Determination of the number, kind, size, and distribution of nonmetallic inclusions in metals.
- **incomplete fusion**
    - In welding, fusion that is less than complete.
- **indentation hardness**
    - (1) The resistance of a material to indentation. This is the usual type of hardness test, in which a pointed or rounded indenter is pressed into a surface under a substantially static load. (2) Resistance of a solid surface to the penetration of a second, usually harder, body under prescribed conditions. Numerical values used to express indentation hardness are not absolute physical quantities, but depend on the hardness scale used to express hardness. See also Brinell hardness test , Knoop hardness test , nanohardness test , Rockwell hardness test , and Vickers hardness test .
- **indenter**
    - In hardness testing, a solid body of prescribed geometry, usually chosen for its high hardness, that is used to determine the resistance of a solid surface to penetration.
- **indigenous inclusion**
    - An inclusion that is native, innate, or inherent in the molten metal treatment. Indigenous inclusions include sulfides, nitrides, and oxides derived from the chemical reaction of the molten metal with the local environment. Such inclusions are small and require microscopic magnification for identification. Compare with exogenous inclusion .
- **indirect-arc furnace**
    - An electric arc furnace in which the metallic charge is not one of the poles of the arc.
- **indirect (backward) extrusion**
    - See extrusion .
- **induction brazing**
    - A brazing process in which the heat required is obtained from the resistance of the workpieces to induced electric current.
- **induction furnace**
    - An alternating current electric furnace in which the primary conductor is coiled and generates, by electromagnetic induction, a secondary current that develops heat within the metal charge.
- **induction hardening**
    - A surface-hardening process in which only the surface layer of a suitable ferrous workpiece is heated by electromagnetic induction to above the upper critical temperature and immediately quenched.
- **induction heating**

  - Heating by combined electrical resistance and hysteresis losses induced by subjecting a metal to the varying magnetic field surrounding a coil carrying alternating current.
- **induction melting**
  - Melting in an induction furnace.
- **induction soldering**
  - A soldering process in which the heat required is obtained from the resistance of the workpieces to induced electric current.
- **induction tempering**
  - Tempering of steel using low-frequency electrical induction heating.
- **induction welding**
  - A welding process that produces coalescence of metals by the heat obtained from the resistance of the workpieces to the flow of induced high-frequency welding current with or without the application of pressure. The effect of the high-frequency welding current is to concentrate the welding heat at the desired location.
- **induction work coil**
  - The inductor used when induction heating and melting as well as induction welding, brazing, and soldering.
- **inductor**
  - A device consisting of one or more associated windings, with or without a magnetic core, for introducing inductance into an electric circuit.
- **industrial atmosphere**
  - An atmosphere in an area of heavy industry with soot, fly ash, and sulfur compounds as the principal constituents.
- **inert anode**
  - An anode that is insoluble in the electrolyte under the conditions prevailing in the electrolysis.
- **inert gas**
  - (1) A gas, such as helium, argon, or nitrogen, that is stable, does not support combustion, and does not form reaction products with other materials. (2) In welding, a gas that does not normally combine chemically with the base metal or filler metal. See also protective atmosphere .
- **infiltration**
  - The process of filling the pores of a sintered or unsintered compact with a metal or alloy of lower melting temperature.
- **infrared brazing**
  - A brazing process in which the heat required is furnished by infrared radiation.
- **infrared soldering**
  - A soldering process in which the heat required is furnished by infrared radiation.
- **infrared spectroscopy**
  - The study of the interaction of material systems with electromagnetic radiation in the infrared region of the spectrum. The technique is useful for determining the molecular structure of organic and inorganic compounds by identifying the rotational and vibrational energy levels associated with the various molecules. See also electromagnetic radiation .
- **ingate**
  - Same as gate .
- **ingot**
  - A casting of simple shape, suitable for hot working or remelting.
- **ingot iron**
  - Commercially pure iron.
- **inhibitor**
  - A substance that retards some specific chemical reaction, e.g., corrosion. Pickling inhibitors retard the dissolution of metal without hindering the removal of scale from steel.
- **inoculant**
  - Material that, when added to molten metal, modifies the structure and thus changes the physical and mechanical properties to a degree not explained on the basis of the change in composition resulting from their use. Ferrosilicon-base alloys are commonly used to inoculate gray irons and ductile irons.
- **inoculation**
  - The addition of a material to molten metal to form nuclei for crystallization. See also inoculant .
- **insert**

    - (1) A part formed from a second material, usually a metal, which is placed in the molds and appears as an integral structural part of the final casting. (2) A removable portion of a die or mold.
- **insert die**
    - A relatively small die that contains part or all of the impression of a forging and that is fastened to a master die block.
- **inserted-blade cutters**
    - Cutters having replaceable blades that are either solid or tipped and are usually adjustable.
- **instrumented impact test**
    - An impact test in which the load on the specimen is continually recorded as a function of time and/or specimen deflection prior to fracture.
- **intense quenching**
    - Quenching in which the quenching medium is cooling the part at a rate at least two and a half times faster than still water. See also Grossmann number .
- **intercept method**
    - A quantitative metallographic technique in which the desired quantity, such as grain size or inclusion content, is expressed as the number of times per unit length a straight line on a metallographic image crosses particles of the feature being measured.
- **interconnected porosity**
    - A network of connecting pores in a sintered object that permits a fluid or gas to pass through the object. Also referred to as interlocking or open porosity.
- **intercritical annealing**
    - Any annealing treatment that involves heating to, and holding at, a temperature between the upper and lower critical temperatures to obtain partial austenitization, followed by either slow cooling or holding at a temperature below the lower critical temperature.
- **intercrystalline**
    - Between the crystals, or grains, of a polycrystalline material.
- **intercrystalline corrosion**
    - See intergranular corrosion .
- **intercrystalline cracking**
    - See intergranular cracking .
- **interdendritic corrosion**
    - Corrosive attack that progresses preferentially along interdendritic paths. This type of attack results from local differences in composition, such as coring commonly encountered in alloy castings.
- **interdendritic porosity**
    - Voids occurring between the dendrites in cast metal.
- **interface**
    - The boundary between any two phases. Among the three phases (gas, liquid, and solid), there are five types of interfaces: gas-liquid, gas-solid, liquid-liquid, liquid-solid, and solid-solid.
- **interfacial tension**
    - The contractile force of an interface between two phases.
- **intergranular**
    - Between crystals or grains. Also called intercrystalline. Contrast with transgranular .
- **intergranular corrosion**
    - Corrosion occurring preferentially at grain boundaries, usually with slight or negligible attack on the adjacent grains. See also interdendritic corrosion .
- **intergranular cracking**
    - Cracking or fracturing that occurs between the grains or crystals in a polycrystalline aggregate. Also called intercrystalline cracking. Contrast with transgranular cracking .
- **intergranular fracture**
    - Brittle fracture of a polycrystalline material in which the fracture is between the grains, or crystals, that form the material. Also called intercrystalline fracture. Contrast with transgranular fracture .
- **intergranular penetration**
    - In welding, the penetration of a filler metal along the grain boundaries of a base metal.
- **intergranular stress-corrosion cracking (IGSCC)**
    - Stress-corrosion cracking in which the cracking occurs along grain boundaries.

- **intermediate annealing**
  - Annealing wrought metals at one or more stages during manufacture and before final treatment.
- **intermediate electrode**
  - Same as bipolar electrode .
- **intermediate phase**
  - In an alloy or a chemical system, a distinguishable homogeneous phase whose composition range does not extend to any of the pure components of the system.
- **intermetallic compound**
  - An intermediate phase in an alloy system, having a narrow range of homogeneity and relatively simple stoichiometric proportions; the nature of the atomic binding can be of various types, ranging from metallic to ionic.
- **intermetallic phases**
  - Compounds, or intermediate solid solutions, containing two or more metals, which usually have compositions, characteristic properties, and crystal structures different from those of the pure components of the system.
- **intermittent weld**
  - A weld in which the continuity is broken by recurring unwelded spaces.
- **internal friction**
  - The conversion of energy into heat by a material subjected to fluctuating stress.
- **internal grinding**
  - Grinding an internal surface such as that inside a cylinder or hole.
- **internal oxidation**
  - The formation of isolated particles of corrosion products beneath the metal surface. This occurs as the result of preferential oxidation of certain alloy constituents by inward diffusion of oxygen, nitrogen, sulfur, and so forth. Also called subscale formation.
- **internal shrinkage**
  - A void or network of voids within a casting caused by inadequate feeding of that section during solidification.
- **internal stress**
  - See preferred term residual stress .
- **interpass temperature**
  - In a multiple-pass weld, the temperature (minimum or maximum as specified) of the deposited weld metal before the next pass is started.
- **interrupted aging**
  - Aging at two or more temperatures, by steps, and cooling to room temperature after each step. See also aging , and compare with progressive aging and step aging .
- **interrupted-current plating**
  - Plating in which the flow of current is discontinued for periodic short intervals to decrease anode polarization and elevate the critical current density. It is most commonly used in cyanide copper plating.
- **interrupted quenching**
  - A quenching procedure in which the workpiece is removed from the first quench at a temperature substantially higher than that of the quenchant and is then subjected to a second quenching system having a different cooling rate than the first.
- **interstitial solid solution**
  - A type of solid solution that sometimes forms in alloy systems having two elements of widely different atomic sizes. Elements of small atomic size, such as carbon, hydrogen, and nitrogen, often dissolve in solid metals to form this solid solution. The space lattice is similar to that of the pure metal, and the atoms of carbon, hydrogen, and nitrogen occupy the spaces or interstices between the metal atoms. See also substitutional solid solution .
- **intracrystalline**
  - Within or across the crystals or grains of a metal; same as transcrystalline and transgranular.
- **intracrystalline cracking**
  - See transgranular cracking .
- **inverse chill**
  - The condition in a casting section in which the interior is mottled or white, while the other sections are gray iron. Also known as reverse chill, internal chill, and inverted chill.
- **inverse segregation**

  - A concentration of low-melting constituents in those regions of an alloy in which solidification first occurs.
- **investing**
  - In investment casting, the process of pouring the investment slurry into a flask surrounding the pattern to form the mold.
- **investment**
  - A flowable mixture, or slurry, of a graded refractory filler, a binder, and a liquid vehicle that, when poured around the patterns, conforms to their shape and subsequently sets hard to form the investment mold.
- **investment casting**
  - (1) Casting metal into a mold produced by surrounding, or investing, an expendable pattern with a refractory slurry coating that sets at room temperature, after which the wax or plastic pattern is removed through the use of heat prior to filling the mold with liquid metal. Also called precision casting or lost wax process . (2) A part made by the investment casting process.
- **investment compound**
  - A mixture of a graded refractory filler, a binder, and a liquid vehicle, used to make molds for investment casting.
- **investment precoat**
  - An extremely fine investment coating applied as a thin slurry directly to the surface of the pattern to reproduce maximum surface smoothness. The coating is surrounded by a coarser, cheaper, and more permeable investment to form the mold. See also dip coat and investment casting .
- **investment shell**
  - Ceramic mold obtained by alternately dipping a pattern set up in dip coat slurry and stuccoing with coarse ceramic particles until the shell of desired thickness is obtained. See also investment casting .
- **ion**
  - An atom, or group of atoms, which by loss or gain of one or more electrons has acquired an electric charge. If the ion is formed from an atom of hydrogen or an atom of a metal, it is usually positively charged; if the ion is formed from an atom of a nonmetal or from a group of atoms, it is usually negatively charged. The number of electronic charges carried by an ion is termed its electrovalence. The charges are denoted by superscripts that give their sign and number; for example, a sodium ion, which carries one positive charge, is denoted by Na^+; a sulfate ion, which carries two negative charges, by SO_4^{2-} .
- **ion carburizing**
  - A method of surface hardening in which carbon ions are diffused into a workpiece in a vacuum through the use of high-voltage electrical energy. Synonymous with plasma carburizing or glow-discharge carburizing.
- **ion exchange**
  - The reversible interchange of ions between a liquid and solid, with no substantial structural changes in the solid.
- **ion implantation**
  - The process of modifying the physical or chemical properties of the near surface of a solid (target) by embedding appropriate atoms into it from a beam of ionized particles.
- **ion nitriding**
  - A method of surface hardening in which nitrogen ions are diffused into a workpiece in a vacuum through the use of high-voltage electrical energy. Synonymous with plasma nitriding or glow-discharge nitriding.
- **ion plating**
  - A generic term applied to atomistic film deposition processes in which the substrate surface and/or the depositing film is subjected to a flux of high-energy particles (usually gas ions) sufficient to cause changes in the interfacial region or film properties.
- **iron casting**
  - A part made of cast iron.
- **ironing**
  - An operation used to increase the length of a tube or cup through reduction of wall thickness and outside diameter, the inner diameter remaining unchanged.
- **iron rot**

  - Deterioration of wood in contact with iron-base alloys.
- **iron soldering**
  - A soldering process in which the heat required is obtained from a soldering iron .
- **irradiation**
  - The exposure of a material or object to x-rays, gamma rays, ultraviolet rays, or other ionizing radiation.
- **isocorrosion diagram**
  - A graph or chart that shows constant corrosion behavior with changing solution (environment) composition and temperature.
- **isomorphous**
  - Having the same crystal structure. This usually refers to intermediate phases that form a continuous series of solid solutions.
- **isostatic pressing**
  - A process for forming a powder metallurgy compact by applying pressure equally from all directions to metal powder contained in a sealed flexible mold. See also cold isostatic pressing and hot isostatic pressing .
- **isothermal annealing**
  - Austenitizing a ferrous alloy, then cooling to and holding at a temperature at which austenite transforms to a relatively soft ferrite-carbide aggregate. See also austenitizing .
- **isothermal forging**
  - A hot-forging process in which a constant and uniform temperature is maintained in the workpiece during forging by heating the dies to the same temperature as the workpiece. Compare with hot-die forging .
- **isothermal transformation**
  - A change in phase that takes place at a constant temperature. The time required for transformation to be completed, and in some instances the time delay before transformation begins, depends on the amount of supercooling below (or superheating above) the equilibrium temperature for the same transformation.
- **isothermal transformation (IT) diagram**
  - A diagram that shows the isothermal time required for transformation of austenite to begin and to finish as a function of temperature. Same as time-temperature-transformation (TTT) diagram or S-curve.
- **isotropic**
  - Having uniform properties in all directions. The measured properties of an isotropic material are independent of the axis of testing.
- **isotropy**
  - The condition of having the same values of properties in all directions.
- **Izod test**
  - A type of impact test in which a V-notched specimen, mounted vertically, is subjected to a sudden blow delivered by the weight at the end of a pendulum arm. The energy required to break off the free end is a measure of the impact strength or toughness of the material. Contrast with Charpy test .
- **J**
- **jaw crusher**
  - A machine for the primary disintegration of metal pieces, ores, or agglomerates into coarse powder.
- **jig**
  - A mechanism for holding a part and guiding the tool during machining or assembly operation.
- **jig boring**
  - Boring with a single-point tool where the work is positioned upon a table that can be located so as to bring any desired part of the work under the tool. Thus, holes can be accurately spaced. This type of boring can be done on milling machines or jig borers.
- **J-integral**
  - A mathematical expression; a line or surface integral that encloses the crack front from one crack surface to the other, used to characterize the fracture toughness of a material having appreciable plasticity before fracture. The *J*-integral eliminates the need to describe the behavior of the material near the crack tip by considering the local stress-strain field around the crack front; J_{Ic} is the critical value of the *J*-integral required to initiate growth of a preexisting crack.

- **joint**
  - The location where two or more members are to be or have been fastened together mechanically or by welding, brazing, soldering, or adhesive bonding.
- **joint clearance**
  - The distance between the faying surfaces of a joint. In brazing, this distance is referred to as that which is present before brazing, at the brazing temperature, or after brazing is completed.
- **joint efficiency**
  - The ratio of the strength of a welded joint to the strength of the base metal, expressed in percent.
- **jolt ramming**
  - Packing sand in a mold by raising and dropping the sand, pattern, and flask on a table. Jolt-type, jolt squeezers, jarring machines, and jolt rammers are machines using this principle. Also called jar ramming.
- **Jominy test**
  - See end-quench hardenability test.
- **K**
- **karat**
  - A unit for designating the fineness of gold in an alloy. In this system, 24 karat (24 k) is 1000 fine or pure gold. The most popular jewelry golds are:

Karat designation	Gold content
24k	100% Au (99.5% min)
18k	18/24ths, or 75% Au
14k	14/24ths or 58.33% Au
10k	10/24ths, or 41.67% Au

- **keel block**
  - A standard test casting, for steel and other high-shrinkage alloys, consisting of a rectangular bar that resembles the keel of a boat, attached to the bottom of a large riser, or shrinkhead. Keel blocks that have only one bar are often called Y-blocks; keel blocks having two bars, double keel blocks. Test specimens are machined from the rectangular bar, and the shrinkhead is discarded.
- **kerf**
  - The width of the cut produced during a cutting process.
- **keyhole**
  - A technique of welding in which a concentrated heat source, such as a plasma arc, penetrates completely through a workpiece forming a hole at the leading edge of the molten weld metal. As the heat source progresses, the molten metal fills in behind the hold to form the weld bead.
- **keyhole specimen**
  - A type of specimen containing a hole-and-slot notch, shaped like a keyhole, usually used in impact bend tests. See also Charpy test and Izod test .
- **killed steel**
  - Steel treated with a strong deoxidizing agent such as silicon or aluminum in order to reduce the oxygen content to such a level that no reaction occurs between carbon and oxygen during solidification.
- **kiln**
  - A large furnace used for baking, drying, or burning firebrick or refractories, or for calcining ores or other substances.
- **K_{Iscc}**
  - Abbreviation for the critical value of the plane strain stress-intensity factor that will produce crack propagation by stress-corrosion cracking of a given material in a given environment.
- **kish**
  - Free graphite that forms in molten hypereutectic cast iron as it cools. In castings, the kish may segregate toward the cope surface, where it lodges at or immediately beneath the casting surface.
- **knife-line attack**

  - Intergranular corrosion of an alloy, usually stabilized stainless steel, along a line adjoining or in contact with a weld after heating into the sensitization temperature range.
- **knockout**
  - (1) Removal of sand cores from a casting. (2) Jarring of an investment casting mold to remove the casting and investment from the flask. (3) A mechanism for freeing formed parts from a die used for stamping, blanking, drawing, forging, or heading operations. (4) A partially pierced hole in a sheet metal part, where the slug remains in the hole and can be forced out by hand if a hole is needed.
- **Knoop hardness number (HK)**
  - A number related to the applied load and to the projected area of the permanent impression made by a rhombic-based pyramidal diamond indenter having included edge angles of 172° 30' and 130° 0' computed from the equation:

$$\mathrm{HK} = \frac{P}{0.07028\,d^2}$$

  - where *P* is applied load, kgf; and *d* is the length of the long diagonal of the impression, mm. In reporting Knoop hardness numbers, the test load is stated.
- **Knoop hardness test**
  - An indentation hardness test using calibrated machines to force a rhombic-based pyramidal diamond indenter having specified edge angles, under specified conditions, into the surface of the material under test and to measure the long diagonal after removal of the load.
- **knuckle-lever press**
  - A heavy short-stroke press in which the slide is directly actuated by a single toggle joint that is opened and closed by a connection and crack. It is used for embossing, coining, sizing, heading, swaging, and extruding.
- **knurling**
  - Impressing a design into a metallic surface, usually by means of small, hard rollers that carry the corresponding design on their surfaces.
- **Kroll process**
  - A process for the production of metallic titanium sponge by the reduction of titanium tetrachloride with a more active metal, such as magnesium or sodium. The sponge is further processed to granules or powder.
- **L**
- **lack of fusion (LOF)**
  - A condition in a welded joint in which fusion is less than complete.
- **lack of penetration (LOP)**
  - A condition in a welded joint in which joint penetration is less than that specified.
- **ladle**
  - Metal receptacle frequently lined with refractories used for transporting and pouring molten metal.
- **ladle metallurgy**
  - Degassing processes for steel carried out in a ladle.
- **lamellar tearing**
  - Occurs in the base metal adjacent to weldments due to high through-thickness strains introduced by weld metal shrinkage in highly restrained joints. Tearing occurs by decohesion and linking along the working direction of the base metal; cracks usually run roughly parallel to the fusion line and are steplike in appearance.
- **laminate**
  - (1) A composite metal, usually in the form of flat sheets, composed of two or more metal layers so bonded that the composite metal forms a structural member. (2) To form a metallic product of two or more bonded layers.
- **lamination**
  - (1) A type of discontinuity with separation or weakness generally aligned parallel to the worked surface of a metal. May be the result of pipe, blisters, seams, inclusions, or segregation elongated and made directional by working. Laminations may also occur in powder metallurgy compacts.

(2) In electrical products such as motors, a blanked piece of electrical sheet that is stacked up with several other identical pieces to make a stator or rotor.

- **lancing**
    - (1) A press operation in which a single-line cut is made in strip stock without producing a detached slug. Chiefly used to free metal for forming, or to cut partial contours for blanked parts, particularly in progressive dies. (2) A piercing (cutting) process carried out by metal powder cutting or oxyfuel gas cutting.
- **land**
    - (1) For profile-sharpened milling cutters, the relieved portion immediately behind the cutting edge. (2) For reamers, drills, and taps, the solid section between the flutes. (3) On punches, the portion adjacent to the nose that is parallel to the axis and of maximum diameter.
- **lap**
    - A surface imperfection, with the appearance of a seam, caused by hot metal, fins, or sharp corners being folded over and then being rolled or forged into the surface but without being welded.
- **lapping**
    - A finishing operation using fine abrasive grits loaded into a lapping material such as cast iron. Lapping provides major refinements in the workpiece including extreme accuracy of dimension, correction of minor imperfections of shape, refinement of surface finish, and close fit between mating surfaces.
- **laser**
    - A device that produces a concentrated coherent light beam by stimulating electronic or molecular transitions to lower energy levels. Laser is an acronym for light amplification by stimulated emission of radiation.
- **laser alloying**
    - See laser surface processing .
- **laser beam cutting**
    - A thermal cutting process that severs materials by melting or vaporizing them with the heat obtained from a laser beam, with or without the application of gas jets to augment the removal of material.
- **laser beam machining**
    - Use of a highly focused monofrequency collimated beam of light to melt or sublime material at the point of impingement on a workpiece.
- **laser beam welding (LBW)**
    - A welding process that produces coalescence of materials with the heat obtained from the application of a concentrated coherent light beam impinging upon the joint.
- **laser hardening**
    - A surface-hardening process that uses a laser to quickly heat a surface. Heat conduction into the interior of the part will quickly cool the surface, leaving a shallow martensitic layer.
- **laser surface processing**
    - The use of lasers with continuous outputs of 0.5 to 10 kW to modify the metallurgical structure of a surface and to tailor the surface properties without adversely affecting the bulk properties. The surface modification can take the following three forms. The first is transformation hardening in which a surface is heated so that thermal diffusion and solid-state transformations can take place. The second is surface melting, which results in a refinement of the structure due to the rapid quenching from the melt. The third is surface (laser) alloying, in which alloying elements are added to the melt pool to change the composition of the surface. The novel structures produced by laser surface melting and alloying can exhibit improved electrochemical and tribological behavior.
- **latent heat**
    - Thermal energy absorbed or released when a substance undergoes a phase change.
- **lateral extrusion**
    - An operation in which the product is extruded sideways through an orifice in the container wall.
- **lath martensite**
    - Martensite formed partly in steels containing less than approximately 1.0% C and solely in steels containing less than approximately 0.5% C as parallel arrays of packets of lath-shape units 0.1 to 0.3 μm thick.
- **lattice constants**
    - See lattice parameter .

- **lattice parameter**
  - The length of any side of a unit cell of a given crystal structure. The term is also used for the fractional coordinates *x*, *y*, and *z* of lattice points when these are variable.
- **launder**
  - (1) A channel for transporting molten metal. (2) A box conduit conveying particles suspended in water.
- **lay**
  - Direction of predominant surface pattern remaining after cutting, grinding, lapping, or other processing.
- **lead**
  - (1) The axial advance of a helix in one complete turn. (2) The slight bevel at the outer end of a face cutting edge of a face mill.
- **lead angle**
  - In cutting tools, the helix angle of the flutes.
- **lead burning**
  - A misnomer for welding of lead.
- **leak testing**
  - A nondestructive test for determining the escape or entry of liquids or gases from pressurized or into evacuated components or systems intended to hold these liquids. Leak testing systems, which employ a variety of gas detectors, are used for locating (detecting and pinpointing) leaks, determining the rate of leakage from one leak or from a system, or monitoring for leakage.
- **ledeburite**
  - The eutectic of the iron-carbon system, the constituents of which are austenite and cementite. The austenite decomposes into ferrite and cementite on cooling below Ar_1, the temperature at which transformation of austenite to ferrite or ferrite plus cementite is completed during cooling.
- **left-hand cutting tool**
  - A cutter all of whose flutes twist away in a counterclockwise direction when viewed from either end.
- **Leidenfrost phenomenon**
  - Slow cooling rates associated with a hot vapor blanket that surrounds a part being quenched in a liquid medium such as water. The gaseous vapor envelope acts as an insulator, thus slowing the cooling rate.
- **leveler lines**
  - Lines on sheet or strip running transverse to the direction of roller leveling. These lines may be seen upon stoning or light sanding after leveling (but before drawing) and can usually be removed by moderate stretching.
- **leveling**
  - Flattening of rolled sheet, strip, or plate by reducing or eliminating distortions. See also stretcher leveling and roller leveling.
- **levigation**
  - (1) Separation of fine powder from coarser material by forming a suspension of the fine material in a liquid. (2) A means of classifying a material as to particle size by the rate of settling from a suspension.
- **levitation melting**
  - An induction melting process in which the metal being melted is suspended by the electromagnetic field and is not in contact with a container.
- **light drawn**
  - An imprecise term, applied to drawn products such as wire and tubing, that indicates a lesser amount of cold reduction than for hard drawn products.
- **lightly coated electrode**
  - A filler-metal electrode used in arc welding, consisting of a metal wire with a light coating, usually of metal oxides and silicates, applied subsequent to the drawing operation primarily for stabilizing the arc. Contrast with covered electrode .
- **light metal**
  - One of the low-density metals, such as aluminum, magnesium, titanium, beryllium, or their alloys.
- **limiting current density**

  - The maximum current density that can be used to obtain a desired electrode reaction without undue interference such as from polarization.
- **limiting dome height (LDH) test**
  - A mechanical test, usually performed unlubricated on sheet metal, that simulates the fracture conditions in a practical press-forming operation.
- **lineage structure**
  - (1) Deviations from perfect alignment of parallel arms of a columnar dendrite as a result of interdendritic shrinkage during solidification from a liquid. This type of deviation may vary in orientation from a few minutes to as much as two degrees of arc. (2) A type of substructure consisting of elongated subgrains.
- **linear elastic fracture mechanics**
  - A method of fracture analysis that can determine the stress (or load) required to induce fracture instability in a structure containing a cracklike flaw of known size and shape. See also fracture mechanics and stress-intensity factor.
- **linear (tensile or compressive) strain**
  - The change per unit length due to force in an original linear dimension. An increase in length is considered positive.
- **liner**
  - (1) The slab of coating metal that is placed on the core alloy and is subsequently rolled down to clad sheet as a composite. (2) In extrusion, a removable alloy steel cylindrical chamber, having an outside longitudinal taper firmly positioned in the container or main body of the press, into which the billet is placed for extrusion.
- **line reaming**
  - Simultaneous reaming of coaxial holes in various sections of a workpiece with a reamer having cutting faces or piloted surfaces with the desired alignment.
- **lip-pour ladle**
  - Ladle in which the molten metal is poured over a lip, much as water is poured out of a bucket.
- **liquation**
  - (1) The separation of a low-melting constituent of an alloy from the remaining constituents, usually apparent in alloys having a wide melting range. (2) Partial melting of an alloy, usually as a result of coring or other compositional heterogeneities.
- **liquation temperature**
  - The lowest temperature at which partial melting can occur in an alloy that exhibits the greatest possible degree of segregation.
- **liquid carburizing**
  - Surface hardening of steel by immersion into a molten bath consisting of cyanides and other salts.
- **liquid honing**
  - Producing a finely polished finish by directing an air-ejected chemical emulsion containing fine abrasives against the surface to be finished.
- **liquid metal embrittlement (LME)**
  - Catastrophic brittle failure of a normally ductile metal when in contact with a liquid metal and subsequently stressed in tension. See also solid metal embrittlement .
- **liquid nitriding**
  - A method of surface hardening in which molten nitrogen-bearing, fused-salt baths containing both cyanides and cyanates are exposed to parts at subcritical temperatures.
- **liquid nitrocarburizing**
  - A nitrocarburizing process (where both carbon and nitrogen are absorbed into the surface) utilizing molten liquid salt baths below the lower critical temperature.
- **liquid penetrant inspection**
  - A type of nondestructive inspection that locates discontinuities that are open to the surface of a metal by first allowing a penetrating dye or fluorescent liquid to infiltrate the discontinuity, removing the excess penetrant, and then applying a developing agent that causes the penetrant to seep back out of the discontinuity and register as an indication. Liquid penetrant inspection is suitable for both ferrous and nonferrous materials, but is limited to the detection of open surface discontinuities in nonporous solids.
- **liquid phase sintering**
  - Sintering of a compact or loose powder aggregate under conditions where a liquid phase is present during part of the sintering cycle.

- **liquid shrinkage**
  - The reduction in volume of liquid metal as it cools to the liquidus.
- **liquidus**
  - (1) The lowest temperature at which a metal or an alloy is completely liquid.(2) In a phase diagram, the locus of points representing the temperatures at which the various compositions in the system begin to freeze on cooling or finish melting on heating. See also solidus .
- **loading**
  - (1) In cutting, building up of a cutting tool back of the cutting edge by undesired adherence of material removed from the work. (2) In grinding, filling the pores of a grinding wheel with material from the work, usually resulting in a decrease in production and quality of finish. (3) In powder metallurgy, filling of the die cavity with powder.
- **loam**
  - A molding material consisting of sand, silt, and clay, used over brickwork or other structural backup material for making massive castings, usually of iron or steel.
- **local action**
  - Corrosion due to the action of "local cells," that is, galvanic cells resulting from inhomogeneities between adjacent areas on a metal surface exposed to an electrolyte.
- **local cell**
  - A galvanic cell resulting from inhomogeneities between areas on a metal surface in an electrolyte. The inhomogeneities may be of physical or chemical nature in either the metal or its environment.
- **local current density**
  - Current density at a point or on a small area.
- **localized corrosion**
  - Corrosion at discrete sites, for example, crevice corrosion, pitting, and stress-corrosion cracking.
- **localized precipitation**
  - Precipitation from a supersaturated solid solution similar to continuous precipitation , except that the precipitate particles form at preferred locations, such as along slip planes, grain boundaries, or incoherent twin boundaries.
- **lock**
  - In forging, a condition in which the flash line is not entirely in one plane. Where two or more plane changes occur, it is called compound lock. Where a lock is placed in the die to compensate for die shift caused by a steep lock, it is called a counterlock.
- **longitudinal direction**
  - That direction parallel to the direction of maximum elongation in a worked material. See also normal direction and transverse direction .
- **longitudinal field**
  - A magnetic field that extends within a magnetized part from one or more poles to one or more other poles and that is completed through a path external to the part.
- **longitudinal resistance seam welding**
  - The making of a resistance seam weld in a direction essentially parallel to the throat depth of a resistance welding machine.
- **long transverse**
  - See transverse direction .
- **looping mill**
  - An arrangement of hot rolling stands such that a hot bar, while being discharged from one stand, is fed into a second stand in the opposite direction.
- **loose metal**
  - Refers to an area in a formed panel that is not stiff enough to hold its shape, may be confused with oil canning.
- **lost foam casting**
  - An expendable pattern process in which an expandable polystyrene pattern surrounded by the unbonded sand, is vaporized during pouring of the molten metal.
- **lost wax process**
  - An investment casting process in which a wax pattern is used.
- **lot**
  - (1) A specific amount of material produced at one time using one process and constant conditions of manufacture, and offered for sale as a unit quantity. (2) A quantity of material that is thought

to be uniform in one or more stated properties such as isotopic, chemical, or physical characteristics. (3) A quantity of bulk material of similar composition whose properties are under study. Compare with batch .

- **low-alloy steels**
    - A category of ferrous materials that exhibit mechanical properties superior to plain carbon steels as the result of additions of such alloying elements as nickel, chromium, and molybdenum. Total alloy content can range from 2.07% up to levels just below that of stainless steels, which contain a minimum of 10% Cr.
- **low-cycle fatigue**
    - Fatigue that occurs at relatively small numbers of cycles ($<10^4$ cycles). Low-cycle fatigue may be accompanied by some plastic, or permanent, deformation. Compare with high-cycle fatigue .
- **lower ram**
    - The part of a pneumatic or hydraulic press that is moving in a lower cylinder and transmits pressure to the lower punch.
- **low-hydrogen electrode**
    - A covered arc welding electrode that provides an atmosphere around the arc and molten weld metal that is low in hydrogen.
- **low-residual-phosphorus copper**
    - Deoxidized copper with residual phosphorus present in amounts (usually 0.004 to 0.012%) generally too small to decrease appreciably the electrical conductivity of the copper.
- **lubricant**
    - (1) Any substance interposed between two surfaces in relative motion for the purpose of reducing the friction or wear between them. (2) A material applied to dies, molds, plungers, or workpieces that promotes the flow of metal, reduces friction and wear, and aids in the release of the finished part.
- **lubrication**
    - (1) The reduction of frictional resistance and wear, or other forms of surface deterioration, between two load-bearing surfaces by the application of a lubricant. (2) Mixing or incorporating a lubricant with a powder to facilitate compacting and ejecting of the compact from the die cavity; also, applying a lubricant to die walls and/or punch surfaces.
- **Lüders lines**
    - Elongated surface markings or depressions in sheet metal, often visible with the unaided eye, caused by discontinuous (inhomogeneous) yielding. Also known as Lüders bands, Hartmann lines, Piobert lines, or stretcher strains.
- **luster finish**
    - A bright, as-rolled finish, produced on ground metal rolls; it is suitable for decorative painting or plating, but usually must undergo additional surface preparation after forming.
- **M**
- **machinability**
    - The relative ease of machining a metal.
- **machinability index**
    - A relative measure of the machinability of an engineering material under specified standard conditions. Also known as machinability rating.
- **machine forging**
    - Forging performed in upsetters or horizontal forging machines.
- **machine welding**
    - Welding with equipment that performs the welding operation under the constant observation and control of a welding operator. The equipment may or may not load and unload the workpiece. See also automatic welding .
- **machining**
    - Removing material from a metal part, usually using a cutting tool, and usually using a power-driven machine.
- **machining allowance**
    - See finish allowance .
- **machining damage**
    - Irregularities or changes on the surface of a material due to machining or grinding operations that may deleteriously affect the performance of the material/part.
- **machining stress**

  - Residual stress caused by machining.
- **macrograph**
  - A graphic representation of the surface of a prepared specimen at a magnification not exceeding 25×. When photographed, the reproduction is known as a photomacrograph.
- **macrohardness test**
  - A term applied to such hardness testing procedures as the Rockwell or Brinell hardness tests to distinguish them from microindentation hardness tests such as the Knoop or Vickers tests.
- **macroscopic stress**
  - Residual stress in a material in a distance comparable to the gage length of strain measurement devices (as opposed to stresses within very small, specific regions, such as individual grains). Compare with microscopic stress .
- **macroshrinkage**
  - Isolated, clustered, or interconnected voids in a casting that are detectable macroscopically. Such voids are usually associated with abrupt changes in section size and are caused by feeding that is insufficient to compensate for solidification shrinkage.
- **macrostructure**
  - The structure of metals as revealed by macroscopic examination of the etched surface of a polished specimen.
- **magnetically hard alloy**
  - See permanent magnet material .
- **magnetically soft alloy**
  - See soft magnetic material .
- **magnetic-analysis inspection**
  - A nondestructive method of inspection to determine the existence of variations in magnetic flux in ferromagnetic materials of constant cross section, such as might be caused by discontinuities and variations in hardness. The variations are usually indicated by a change in pattern on an oscilloscope screen.
- **magnetic-particle inspection**
  - A nondestructive method of inspection for determining the existence and extent of surface cracks and similar imperfections in ferromagnetic materials. Finely divided magnetic particles, applied to the magnetized part, are attracted to and outline the pattern of any magnetic leakage fields created by discontinuities.
- **magnetic pole**
  - The area on a magnetized part at which the magnetic field leaves or enters the part. It is a point of maximum attraction in a magnet.
- **magnetic separator**
  - A device used to separate magnetic from less magnetic or nonmagnetic materials. The crushed material is conveyed on a belt past a magnet.
- **magnetizing force**
  - A force field, resulting from the flow of electric currents or from magnetized bodies, that produces magnetic induction.
- **magnetostriction**
  - Changes in dimensions of a body resulting from application of a magnetic field.
- **malleability**
  - The characteristic of metals that permits plastic deformation in compression without fracture. See also ductility .
- **malleabilizing**
  - Annealing white iron in such a way that some or all of the combined carbon is transformed into graphite or, in some cases, so that part of the carbon is removed completely.
- **malleable iron**
  - A cast iron made by prolonged annealing of white iron in which decarburization, graphitization, or both take place to eliminate some or all of the cementite. The graphite is in the form of temper carbon. If decarburization is the predominant reaction, the product will exhibit a light fracture surface; hence whiteheart malleable. Otherwise, the fracture surface will be dark; hence blackheart malleable. Only the blackheart malleable is produced in the United States. Ferritic malleable has a predominantly ferritic matrix; pearlitic malleable may contain pearlite, spheroidite, or tempered martensite, depending on heat treatment and desired hardness.
- **mandrel**

    - (1) A blunt-ended tool or rod used to retain the cavity in a hollow metal product during working. (2) A metal bar around which other metal may be cast, bent, formed, or shaped. (3) A shaft or bar for holding work to be machined. (4) A form, such as a mold or matrix, used as a cathode in electroforming.
- **mandrel forging**
    - The process of rolling or forging a hollow blank over a mandrel to produce a weldless, seamless ring or tube. See also radial forging .
- **Mannesmann process**
    - A process for piercing tube billets in making seamless tubing. The billet is rotated between two heavy rolls mounted at an angle and is forced over a fixed mandrel.
- **manual welding**
    - A welding operation performed and controlled completely by hand. See also automatic welding , machine welding , and semiautomatic welding .
- **maraging**
    - A precipitation-hardening treatment applied to a special group of high-nickel iron-base alloys (maraging steels) to precipitate one or more intermetallic compounds in a matrix of essentially carbon-free martensite.
- **Marforming process**
    - A rubber-pad forming process developed to form wrinkle-free shrink flanges and deep-drawn shells. It differs from the Guerin process in that the sheet metal blank is clamped between the rubber pad and the blankholder before forming begins.
- **marquenching**
    - See martempering .
- **martempering**
    - (1) A hardening procedure in which an austenitized ferrous material is quenched into an appropriate medium at a temperature just above the martensite start temperature of the material, held in the medium until the temperature is uniform throughout, although not long enough for bainite to form, then cooled in air. The treatment is frequently followed by tempering. (2) When the process is applied to carburized material, the controlling martensite start temperature is that of the case. This variation of the process is frequently called marquenching.
- **martensite**
    - A generic term for microstructures formed by diffusionless phase transformation in which the parent and product phases have a specific crystallographic relationship. Martensite is characterized by an acicular pattern in the microstructure in both ferrous and nonferrous alloys. In alloys where the solute atoms occupy interstitial positions in the martensitic lattice (such as carbon in iron), the structure is hard and highly strained; but where the solute atoms occupy substitutional positions (such as nickel in iron), the martensite is soft and ductile. The amount of high-temperature phase that transforms to martensite on cooling depends to a large extent on the lowest temperature attained, there being a rather distinct beginning temperature (M_s) and a temperature at which the transformation is essentially complete (M_f). See also lath martensite , plate martensite , and tempered martensite .
- **marsensite range**
    - The interval between the martensite start (M_s) and the martensite finish (M_f) temperatures.
- **martensitic**
    - A platelike constituent having an appearance and a mechanism of formation similar to that of martensite. See also lath martensite and plate martensite .
- **martensitic transformation**
    - A reaction that takes place in some metals on cooling, with the formation of an acicular structure called martensite .
- **master alloy**
    - An alloy, rich in one or more desired addition elements, that is added to a metal melt to raise the percentage of a desired constituent.
- **master alloy powder**
    - A prealloyed metal powder of high concentration of alloy content, designed to be diluted when mixed with a base powder to produce the desired composition. See also prealloyed powder .
- **master pattern**
    - In foundry practice, a pattern embodying a double contraction allowance in its construction, used for making castings to be employed as patterns in production work.

- **match**
  - A condition in which a point in one metalforming or forging die half is aligned properly with the corresponding point in the opposite die half within specified tolerance.
- **matched edges**
  - Two edges of the die face that are machined exactly at 90° to each other, and from which all dimensions are taken in laying out the die impression and aligning the dies in the forging equipment. Also referred to as match lines.
- **match plate**
  - A plate of metal or other material on which patterns for metal casting are mounted (or formed as an integral part) to facilitate molding. The pattern is divided along its parting plane by the plate.
- **materials characterization**
  - The use of various analytical methods (spectroscopy, microscopy, chromatography, etc.) to describe those features of composition (both bulk and surface) and structure (including defects) of a material that are significant for a particular preparation, study of properties, or use. Test methods that yield information primarily related to materials properties, such as thermal, electrical, and mechanical properties, are excluded from this definition.
- **matrix**
  - The continuous or principal phase in which another constituent is dispersed.
- **matte**
  - An intermediate product of smelting ; an impure metallic sulfide mixture made by melting a roasted sulfide ore, such as an ore of copper, lead, or nickel.
- **matte finish**
  - (1) A dull texture produced by rolling sheet or strip between rolls that have been roughened by blasting. (2) A dull finish characteristic of some electrodeposits, such as cadmium or tin.
- **maximum stress (S_{max})**
  - The stress having the highest algebraic value in the stress cycle, tensile stress being considered positive and compressive stress negative. The nominal stress is used most commonly.
- **maximum stress intensity factor (K_{max})**
  - The maximum value of the stress-intensity factor in a fatigue cycle.
- **McQuaid-Ehn grain size**
  - The austenitic grain size developed in steels by carburizing at 927 °C (1700 °F) followed by slow cooling. Eight standard McQuaid-Ehn grain sizes rate the structure, from No. 8, the finest, to No. 1, the coarsest. The use of standardized ASTM methods for determining grain size is recommended.
- **mean stress (S_m)**
  - The algebraic average of the maximum and minimum stresses in one cycle, that is, $S_m = (S_{max} + S_{min})/2$. Also referred to as steady component of stress.
- **mechanical alloying (MA)**
  - An alternate cold welding and shearing of particles of two or more species of greatly differing hardness. The operation is carried out in high-intensity ball mills, such as attritors, and is the preferred method of producing oxide-dispersion-strengthened (ODS) materials. See also attritor grinding and dispersion-strengthened material .
- **mechanical hysteresis**
  - Energy absorbed in a complete cycle of loading and unloading within the elastic limit and represented by the closed loop of the stress-strain curves for loading and unloading. Sometimes referred to as elastic, but more properly, mechanical.
- **mechanical metallurgy**
  - The science and technology dealing with the behavior of metals when subjected to applied forces; often considered to be restricted to plastic working or shaping of metals.
- **mechanical plating**
  - Plating wherein fine metal powders are peened onto the work by tumbling or other means. The process is used primarily to provide ferrous parts with coatings of zinc, cadmium, tin, and alloys of these metals in various combinations.
- **mechanical polishing**
  - A process that yields a specularly reflecting surface entirely by the action of machining tools, which are usually the points of abrasive particles suspended in a liquid among the fibers of a polishing cloth.
- **mechanical press**

  - A press whose slide is operated by a crank, eccentric, cam, toggle links, or other mechanical device.
- **mechanical properties**
  - The properties of a material that reveal its elastic and inelastic behavior when force is applied, thereby indicating its suitability for mechanical applications; for example, modulus of elasticity, tensile strength, elongation, hardness, and fatigue limit. Compare with physical properties .
- **mechanical testing**
  - The methods by which the mechanical properties of a metal are determined.
- **mechanical twin**
  - A twin formed in a crystal by simple shear under external heating.
- **mechanical working**
  - The subjecting of metals to pressure exerted by rolls, hammers, or presses in order to change the shape or physical properties of the metal.
- **median fatigue life**
  - The middle value when all of the observed fatigue life values of the individual specimens in a group tested under identical conditions are arranged in order of magnitude. When an even number of specimens are tested, the average of the two middlemost values is used. Use of the sample median rather than the arithmetic mean (that is, the average) is usually preferred.
- **median fatigue strength at *N* cycles**
  - An estimate of the stress level at which 50% of the population would survive N cycles. The estimate is derived from a particular point of the fatigue life distribution, since there is no test procedure by which a frequency distribution of fatigue strengths at N cycles can be directly observed. Also known as fatigue strength at N cycles .
- **melting point**
  - The temperature at which a pure metal, compound, or eutectic changes from solid to liquid; the temperature at which the liquid and the solid are at equilibrium.
- **melting range**
  - The range of temperatures over which an alloy other than a compound or eutectic changes from solid to liquid; the range of temperatures from solidus to liquidus at any given composition on a phase diagram.
- **melting temperature**
  - See melting point .
- **melt-through**
  - Complete joint penetration for a joint welded from one side.
- **merchant mill (obsolete)**
  - A mill, consisting of a group of stands of three rolls each arranged in a straight line and driven by one power unit, used to roll rounds, squares or flats of smaller dimensions than would be rolled on a bar mill.
- **mesh**
  - (1) The number of screen openings per linear inch of screen; also called *mesh size*. (2) The screen number on the finest screen of a specified standard screen scale through which almost all of the particles of a powder sample will pass. See also sieve analysis and sieve classification .
- **mesh-belt conveyor furnace**
  - A continuously operating furnace that uses a conveyor belt for the transport of the charge.
- **metal**
  - (1) An opaque lustrous elemental chemical substance that is a good conductor of heat and electricity and, when polished, a good reflector of light. Most elemental metals are malleable and ductile and are, in general, denser than the other elemental substances. (2) As to structure, metals may be distinguished from nonmetals by their atomic binding and electron availability. Metallic atoms tend to lose electrons from the outer shells, the positive ions thus formed being held together by the electron gas produced by the separation. The ability of these "free electrons" to carry an electric current, and the fact that this ability decreases as temperature increases, establish the prime distinctions of a metallic solid. (3) From a chemical viewpoint, an elemental substance whose hydroxide is alkaline. (4) An alloy.
- **metal arc cutting**
  - Any of a group of arc cutting processes that severs metals by melting them with the heat of an arc between a metal electrode and the base metal. See also gas metal arc cutting and shielded metal arc cutting .

- **metal arc welding**
    - Any of a group of arc welding processes in which metals are fused together using the heat of an arc between a metal electrode and the work. Use of the specific process name is preferred.
- **metal cored electrode**
    - A composite filler metal welding electrode consisting of a metal tube or other hollow configuration containing alloying ingredients. Minor amounts of ingredients facilitate arc stabilization and fluxing of oxides. External shielding gas may or may not be used.
- **metal dusting**
    - Accelerated deterioration of metals in carbonaceous gases at elevated temperatures to form a dustlike corrosion product.
- **metal electrode**
    - An electrode used in arc welding or cutting that consists of a metal wire or rod that is either bare or covered with a suitable covering or coating.
- **metallic glass**
    - A noncrystalline metal or alloy, commonly produced by drastic supercooling of a molten alloy, by molecular deposition, which involves growth from the vapor phase (e.g., thermal evaporation and sputtering) or from a liquid phase (e.g., electroless deposition and electrodeposition), or by external action techniques (e.g., ion implantation and ion beam mixing).
- **metallizing**
    - Forming a metallic coating by atomized spraying with molten metal or by vacuum deposition. Also called spray metallizing.
- **metallograph**
    - An optical instrument designed for visual observation and photomicrography of prepared surfaces of opaque materials at magnifications of 25 to approximately 2000×. The instrument consists of a high-intensity illuminating source, a microscope, and a camera bellows. On some instruments, provisions are made for examination of specimen surfaces using polarized light, phase contrast, oblique illumination, dark-field illumination, and bright-field illumination.
- **metallography**
    - The study of the structure of metals and alloys by various methods, especially by optical and electron microscopy.
- **metallurgical bond**
    - The principal bond that holds metal together and is formed between base metals and filler metals in all welding processes. This is a primary bond arising from the increased spatial extension of the valence electron wave functions when an aggregate of metal atoms is brought close together. Also referred to as metallic bond.
- **metallurgical coke**
    - A coke, usually low in sulfur, having a very high compressive strength at elevated temperatures; used in metallurgical furnaces not only as fuel, but also to support the weight of the charge.
- **metallurgy**
    - The science and technology of metals and alloys. Process metallurgy is concerned with the extraction of metals from their ores and with refining of metals; physical metallurgy, with the physical and mechanical properties of metals as affected by composition, processing, and environmental conditions; and mechanical metallurgy, with the response of metals to applied forces.
- **metal-matrix composite**
    - A material that consists of a nonmetallic reinforcement, such as ceramic fibers or filaments, incorporated into a metallic matrix.
- **metal penetration**
    - A surface condition in metal castings in which metal or metal oxides have filled voids between sand grains without displacing them.
- **metal powder**
    - Elemental metals or alloy particles, usually in the size range of 0.1 to 1000 μm.
- **metal powder cutting**
    - A technique that supplements an oxyfuel torch with a stream of iron or blended iron-aluminum powder to facilitate flame cutting of difficult-to-cut materials. The powdered material propagates and accelerates the oxidation reaction, as well as the melting and spalling action of the materials to be cut.
- **metal spraying**

  - Coating metal objects by spraying molten metal against their surfaces. See also thermal spraying .
- **metastable**
  - (1) Of a material not truly stable with respect to some transition, conversion, or reaction but stabilized kinetically either by rapid cooling or by some molecular characteristics as, for example, by the extremely high viscosity of polymers. (2) Possessing a state of pseudoequilibrium that has a free energy higher than that of the true equilibrium state.
- **M_f temperature**
  - For any alloy system, the temperature at which martensite formation on cooling is essentially finished. See also transformation temperature for the definition applicable to ferrous alloys.
- **microcrack**
  - A crack of microscopic proportions. Also termed microfissure .
- **microfissure**
  - A crack of microscopic proportions.
- **micrograph**
  - A graphic reproduction of the surface of a specimen at a magnification greater than 25×. If produced by photographic means it is called a photomicrograph (not a microphotograph).
- **microhardness**
  - The hardness of a material as determined by forcing an indenter such as a Vickers or Knoop indenter into the surface of a material under very light load; usually, the indentations are so small that they must be measured with a microscope. Capable of determining hardnesses of different microconstituents within a structure, or of measuring steep hardness gradients such as those encountered in case hardening. See also microhardness test .
- **microhardness number**
  - A commonly used term for the more technically correct term microindentation hardness number .
- **microhardness test**
  - A microindentation hardness test using a calibrated machine to force a diamond indenter of specific geometry, under a test load of 1 to 1000 gram-force, into the surface of the test material and to measure the diagonal or diagonals optically. See also Knoop hardness test and Vickers hardness test .
- **microindentation**
  - (1) In hardness testing, the small residual impression left in a solid surface when an indenter, typically a pyramidal diamond stylus, is withdrawn after penetrating the surface. Typically, the dimensions of the microindentations are measured to determine microindentation hardness number. (2) The process of indenting a solid surface, using a hard stylus of prescribed geometry and under a slowly applied normal force, usually for the purpose of determining its microindentation hardness number. See also Knoop hardness number , microindentation hardness number , and Vickers hardness number .
- **microindentation hardness number**
  - A numerical quantity, usually stated in units of pressure (kg/mm^2), that expresses the resistance to penetration of a solid surface by a hard indenter of prescribed geometry and under a specified, slowly applied normal force. The prefix "micro" indicates that the indentations produced are typically between 10.0 and 200.0 μm across. See also Knoop hardness number , nanohardness test , and Vickers hardness number .
- **microscopic**
  - Visible at magnifications above 25×.
- **microscopic stress**
  - Residual stress in a material within a distance comparable to the grain size. See also macroscopic stress .
- **microsegregation**
  - Segregation within a grain, crystal, or small particle. See also coring .
- **microshrinkage**
  - A casting imperfection, not detectable microspically, consisting of interdendritic voids. Microshrinkage results from contraction during solidification where the opportunity to supply filler material is inadequate to compensate for shrinkage. Alloys with wide ranges in solidification temperature are particularly susceptible.
- **microstrain**

    - The strain over a gage length comparable to interatomic distances. These are the strains being averaged by the macrostrain measurement. Microstrain is not measurable by existing techniques. Variance of the microstrain distribution can, however, be measured by x-ray diffraction.
- **microstress**
    - Same as microscopic stress .
- **microstructure**
    - The structure of an object, organism, of material as revealed by a microscope at magnifications greater than 25×.
- **middling**
    - A product intermediate between concentrate and tailing and containing enough of a valuable mineral to make retreatment profitable.
- **MIG welding**
    - Metal inert-gas welding; see preferred term gas metal arc welding .
- **mild steel**
    - Carbon steel with a maximum of about 0.25% C and containing 0.4 to 0.7% Mn, 0.1 to 0.5% Si, and some residuals of sulfur, phosphorus, and/or other elements.
- **mill**
    - (1) A factory in which metals are hot worked, cold worked, or melted and cast into standard shapes suitable for secondary fabrication into commercial products. (2) A production line, usually of four or more stands, for hot or cold rolling metal standard shapes such as bar, rod, plate, sheet, or strip. (3) A single machine or hot rolling, cold rolling, or extruding metal; examples include blooming mill, cluster mill, four-high mill, and Sendzimir mill. (4) A shop term for a milling cutter. (5) A machine or group of machines for grinding or crushing ores and other minerals. (6) A machine for grinding or mixing material, for example, a ball mill and a paint mill. (7) Grinding or mixing a material, for example, milling a powder metallurgy material.
- **mill edge**
    - The normal edge produced in hot rolling of sheet metal. This edge is customarily removed when hot rolled sheets are further processed into cold rolled sheets.
- **Miller indices**
    - A system for identifying planes and directions in any crystal system by means of sets of integers. The indices of a plane are related to the intercepts of that plane with the axes of a unit cell; the indices of a direction, to the multiples of lattice parameter that represent the coordinates of a point on a line parallel to the direction and passing through the arbitrarily chosen origin of a unit cell.
- **mill finish**
    - A nonstandard (and typically nonuniform) surface finish on mill products that are delivered without being subjected to a special surface treatment (other than a corrosion-preventive treatment) after the final working or heat-treating step.
- **milling (machining)**
    - Removing metal with a milling cutter.
- **milling (powder technology)**
    - The mechanical comminution of a material, usually in a ball mill, to alter the size or shape of the individual particles, to coat one component of a mixture with another, or to create uniform distributions of components.
- **milling cutter**
    - A rotary cutting tool provided with one or more cutting elements, called teeth, that intermittently engage the workpiece and remove material by relative movement of the workpiece and cutter.
- **mill product**
    - Any commercial product of a mill.
- **mill scale**
    - The heavy oxide layer that forms during the hot fabrication or heat treatment of metals.
- **mineral dressing**
    - Physical and chemical concentration of raw ore into a product from which a metal can be recovered at a profit.
- **minimized spangle**
    - A hot dip galvanized coating of very small grain size, which makes the spangle less visible when the part is subsequently painted.
- **minimum bend radius**

  - The minimum radius over which a metal product can be bent to a given angle without fracture.
- **minimum stress (S_{min})**
  - In fatigue, the stress having the lowest algebraic value in the cycle, tensile stress being considered positive and compressive stress negative.
- **minimum stress-intensity factor (K_{min})**
  - In fatigue, the minimum value of the stress-intensity factor in a cycle. This value corresponds to the minimum load when the load ratio is >0 and is taken to be zero when the load ratio is ≤ 0.
- **minus sieve**
  - The portion of a powder sample that passes through a standard sieve of a specified number. See also plus sieve and sieve analysis .
- **mischmetal**
  - An natural mixture of rare-earth elements (atomic numbers 57 through 71) in metallic form. It contains about 50% Ce, the remainder being principally lanthanum and neodymium.
- **mismatch**
  - The misalignment or error in register of a pair of forging dies; also applied to the condition of the resulting forging.
- **misrun**
  - Denotes an irregularity on a cast metal surface caused by incomplete filling of the mold due to low pouring temperatures, gas back pressure from inadequate venting of the mold, and inadequate gating.
- **mixed potential**
  - The potential of a specimen (or specimens in a galvanic couple) when two or more electrochemical reactions are occurring. Also called galvanic couple potential.
- **mixing**
  - In powder metallurgy, the thorough intermingling of powders of two or more different materials (not to be confused with blending).
- **modification**
  - Treatment of molten hypoeutectic (8 to 13% Si) or hypereutectic (13 to 19% Si) aluminum-silicon alloys to improve mechanical properties of the solid alloy by refinement of the size and distribution of the silicon phase. Involves additions of small percentages of sodium, strontium, or calcium (hypoeutectic alloys) or of phosphorus (hypereutectic alloys).
- **modulus of elasticity (E)**
  - (1) The measure of rigidity or stiffness of a material; the ratio of stress, below the proportional limit, to the corresponding strain. If a tensile stress of 13.8 MPa (2.0 ksi) results in an elongation of 1.0%, the modulus of elasticity is 13.8 MPa (2.0 ksi) divided by 0.01, or 1380 MPa (200 ksi). (2) In terms of the stress-strain curve, the modulus of elasticity is the slope of the stress-strain curve in the range of linear proportionality of stress to strain. Also known as Young's modulus . For materials that do not conform to Hooke's law throughout the elastic range, the slope of either the tangent to the stress-strain curve at the origin or at low stress, the secant drawn from the origin to any specified point on the stress-strain curve, or the chord connecting any two specific points on the stress-strain curve is usually taken to be the modulus of elasticity. In these cases, the modulus is referred to as the tangent modulus, secant modulus, or chord modulus, respectively.
- **modulus of resilience**
  - The amount of energy stored in a material when loaded to its elastic limit. It is determined by measuring the area under the stress-strain curve up to the elastic limit. See also resilience and strain energy .
- **modulus of rigidity**
  - See shear modulus .
- **modulus of rupture**
  - Nominal stress at fracture in a bend test or torsion test. In bending, modulus of rupture is the bending moment at fracture divided by the section modulus. In torsion, modulus of rupture is the torque at fracture divided by the polar section modulus.
- **Mohs hardness**
  - The hardness of a body according to a scale proposed by Mohs, based on ten minerals, each of which would scratch the one below it. These minerals, in decreasing order of hardness, are:

Diamond	10
Corundum	9
Topaz	8
Quartz	7
Othoclase (feldspar)	6
Apatite	5
Fluorite	4
Calcite	3
Gypsum	2
Talc	1

- **mold**
  - (1) The form, made of sand, metal, or refractory material, that contains the cavity into which molten metal is poured to produce a casting of desired shape. (2) A die.
- **mold cavity**
  - The space in a mold that is filled with liquid metal to form the casting upon solidification. The channel through which liquid metal enters the mold cavity (sprue, runner, gates) and reservoirs for liquid metal (risers) are not considered part of the mold cavity proper.
- **molding machine**
  - A machine for making sand molds by mechanically compacting sand around a pattern.
- **molding press**
  - A press used to form powder metallurgy compacts.
- **molding sands**
  - Foundry sands containing more than 5% natural clay, usually between 8 and 20%.
- **mold jacket**
  - Wood or metal form that is slipped over a sand mold for support during pouring of a casting.
- **mold wash**
  - An aqueous or alcoholic emulsion or suspension of various materials used to coat the surface of a casting mold cavity.
- **molten weld pool**
  - The liquid state of a weld prior to solidification as weld metal.
- **Mond process**
  - A process for extracting and purifying nickel. The main features consist of forming nickel carbonyl by reaction of finely divided reduced metal with carbon monoxide, then decomposing the nickel carbonyl to deposit purified nickel on small nickel pellets.
- **monotectic**
  - An isothermal reversible reaction in a binary system, in which a liquid on cooling decomposes into a second liquid of a different composition and a solid. It differs from a eutectic in that only one of the two products of the reaction is below its freezing range.
- **monotropism**
  - The ability of a solid to exist in two or more forms (crystal structures), but in which one form is the stable modification at all temperatures and pressures. Ferrite and martensite are a monotropic pair below the temperature at which austenite begins to form, for example, in steels. Alternate spelling is monotrophism.
- **morphology**
  - The characteristic shape, form, or surface texture or contours of the crystals, grains, or particles of (or in) a material, generally on a microscopic scale.
- **mosaic structure**
  - In crystals, a substructure in which adjoining regions have only slightly different orientations.
- **mottled cast iron**
  - Iron that consists of a mixture of variable proportions of gray cast iron and white cast iron; such a material has a mottled fracture appearance.
- **mounting**

  - A means by which a specimen for metallographic examination may be held during preparation of a section surface. The specimen can be embedded in plastic or secured mechanically in clamps.
- **mounting resin**
  - Thermosetting or thermoplastic resins used to mount metallographic specimens.
- **M_s temperature**
  - For any alloy system, the temperature at which martensite starts to form on cooling. See transformation temperature for the definition applicable to ferrous alloys.
- **mulling**
  - The mixing and kneading of foundry molding sand with moisture and clay to develop suitable properties for molding.
- **multiaxial stresses**
  - Any stress state in which two or three principal stresses are not zero.
- **multiple**
  - A piece of stock for forging that is cut from bar or billet lengths to provide the exact amount of material for a single workpiece.
- **multiple-pass weld**
  - A weld made by depositing filler metal with two or more successive passes.
- **multiple-slide press**
  - A press with individual slides, built into the main slide or connected to individual eccentrics on the main shaft, that can be adjusted to vary the length of stroke and the timing. See also slide .
- **multiple spot welding**
  - Spot welding in which several spots are made during one complete cycle of the welding machine.
- ***m*-value**
  - See strain-rate sensitivity .
- **N**
- **nanohardness test**
  - An indentation hardness testing procedure, usually relying on indentation force versus tip displacement data, to make assessments of the resistance of surfaces to penetrations of the order of 10 to 1000 nm deep.
- **native metal**
  - (1) Any deposit in the earth's crust consisting of uncombined metal. (2) The metal in such a deposit.
- **natural aging**
  - Spontaneous aging of a supersaturated solid solution at room temperature. See also aging . Compare with artificial aging .
- **natural strain**
  - See true strain .
- **NDE**
  - See nondestructive evaluation .
- **NDI**
  - See nondestructive inspection .
- **NDT**
  - See nondestructive testing .
- **near-net shape**
  - See net shape .
- **necking**
  - (1) The reduction of the cross-sectional area of a material in a localized area by uniaxial tension or by stretching. (2) The reduction of the diameter of a portion of the length of a cylindrical shell or tube.
- **necking down**
  - Localized reduction in area of a specimen during tensile deformation.
- **net shape**
  - The shape of a powder metallurgy part, casting, or forging that conforms closely to specified dimensions. Such a part requires no secondary machining or finishing. A near-net shape part can be either one in which some but not all of the surfaces are net or one in which the surfaces require only minimal machining or finishing.
- **Neumann band**

    - Mechanical twin in ferrite.
- **neutral flame**
    - (1) A gas flame in which there is no excess of either fuel or oxygen in the inner flame. Oxygen from ambient air is used to complete the combustion of CO_2 and H_2 produced in the inner flame. (2) An oxyfuel gas flame in which the portion used is neither oxidizing nor reducing. See also carburizing flame , oxidizing flame , and reducing flame .
- **neutron embrittlement**
    - Embrittlement resulting from bombardment with neutrons, usually encountered in metals that have been exposed to a neutron flux in the core of the reactor. In steels, neutron embrittlement is evidenced by a rise in the ductile-to-brittle transition temperature.
- **nibbling**
    - Contour cutting of sheet metal by use of a rapidly reciprocating punch that makes numerous small cuts.
- **nip angle**
    - See angle of bite .
- **nitriding**
    - Introducing nitrogen into the surface layer of a solid ferrous alloy by holding at a suitable temperature (below Ac_1 for ferritic steels) in contact with a nitrogenous material, usually ammonia or molten cyanide of appropriate composition. Quenching is not required to produce a hard case. See also bright nitriding and liquid nitriding .
- **nitrocarburizing**
    - Any of several processes in which both nitrogen and carbon are absorbed into the surface layers of a ferrous material at temperatures below the lower critical temperature and, by diffusion, create a concentration gradient. Nitrocarburizing is performed primarily to provide an antiscuffing surface layer and to improve fatigue resistance. Compare with carbonitriding .
- **noble**
    - The positive direction of electrode potential, thus resembling noble metals such as gold and platinum.
- **noble metal**
    - (1) A metal whose potential is highly positive relative to the hydrogen electrode. (2) A metal with marked resistance to chemical reaction, particularly to oxidation and to solution by inorganic acids. The term as often used is synonymous with precious metal .
- **noble potential**
    - A potential more cathodic (positive) than the standard hydrogen potential.
- **no-draft (draftless) forging**
    - A forging with extremely close tolerances and little or no draft that requires minimal machining to produce the final part. Mechanical properties can be enhanced by closer control of grain flow and by retention of surface material in the final component.
- **nodular graphite**
    - Graphite in nodular (rounded) form as opposed to flake form (see flake graphite). See also ductile iron and spheroidal graphite .
- **nodular iron**
    - See preferred term ductile iron.
- **nominal stress**
    - The stress at a point calculated on the net cross section without taking into consideration the effect on stress of geometric discontinuities, such as holes, grooves, fillets, and so forth. The calculation is made using simple elastic theory.
- **nondestructive evaluation (NDE)**
    - Broadly considered synonymous with nondestructive inspection (NDI) . More specifically, the quantitative analysis of NDI findings to determine whether the material will be acceptable for its function, despite the presence of discontinuities. With NDE, a discontinuity can be classified by its size, shape, type, and location, allowing the investigator to determine whether or not the flaw(s) is acceptable. Damage tolerant design approaches are based on the philosophy of ensuring safe operation in the presence of flaws.
- **nondestructive inspection (NDI)**
    - A process or procedure, such as ultrasonic or radiographic inspection, for determining the quality or characteristics of a material, part, or assembly, without permanently altering the subject or its

properties. Used to find internal anomalies in a structure without degrading its properties or impairing its serviceability.

- **nondestructive testing (NDT)**
  - Broadly considered synonymous with nondestructive inspection (NDI).
- **nonmetallic inclusions**
  - See inclusions .
- **normal direction**
  - That direction perpendicular to the plane of working in a worked material. See also longitudinal direction and transverse direction .
- **normalizing**
  - Heating a ferrous alloy to a suitable temperature above the transformation range and then cooling in air to a temperature substantially below the transformation range.
- **normal segregation**
  - Concentration of alloying constituents that have low melting points in those portions of a casting that solidify last. Compare with inverse segregation .
- **normal solution**
  - An aqueous solution containing one gram equivalent of the active reagent in 1 L of the solution.
- **normal stress**
  - The stress component that is perpendicular to the plane on which the forces act. Normal stress may be either tensile or compressive.
- **nose radius**
  - The radius of the rounded portion of the cutting edge of a tool.
- **notch acuity**
  - Relates to the severity of the stress concentration produced by a given notch in a particular structure. If the depth of the notch is very small compared with the width (or diameter) of the narrowest cross section, acuity may be expressed as the ratio of the notch depth to the notch root radius. Otherwise, acuity is defined as the ratio of one-half the width (or diameter) of the narrowest cross section to the notch root radius.
- **notch brittleness**
  - Susceptibility of a material to brittle fracture at points of stress concentration. For example, in a notch tensile test, the material is said to be notch brittle if the notch strength is less than the tensile strength of an unnotched specimen. Otherwise, it is said to be notch ductile.
- **notch depth**
  - The distance from the surface of a test specimen to the bottom of the notch. In a cylindrical test specimen, the percentage of the original cross-sectional area removed by machining an annular groove.
- **notch ductility**
  - The percentage reduction in area after complete separation of the metal in a tensile test of a notched specimen.
- **notched specimen**
  - A test specimen that has been deliberately cut or notched, usually in a V-shape, to induce and locate point of failure.
- **notch factor**
  - Ratio of the resilience determined on a plain specimen to the resilience determined on a notched specimen.
- **notching**
  - Cutting out various shapes from the edge of a strip, blank, or part.
- **notching press**
  - A mechanical press used for notching internal and external circumferences and also for notching along a straight line. These presses are equipped with automatic feeds because only one notch is made per stroke.
- **notch rupture strength**
  - The ratio of applied load to original area of the minimum cross section in a stress-rupture test of a notched specimen.
- **notch sensitivity**
  - The extent to which the sensitivity of a material to fracture is increased by the presence of a stress concentration, such as a notch, a sudden change in cross section, a crack, or a scratch. Low notch

sensitivity is usually associated with ductile materials, and high notch sensitivity is usually associated with brittle materials.

- **notch strength**
  - The maximum load on a notched tension-test specimen divided by the minimum cross-sectional area (the area at the root of the notch). Also called notch tensile strength.
- **nuclear grade**
  - Material of a quality adequate for use in nuclear application.
- **nucleation**
  - The initiation of a phase transformation at discrete sites, with the new phase growing on the nuclei. See also nucleus (2) .
- **nucleus**
  - (1) The heavy central core of an atom, in which most of the mass and the total positive electric charge are concentrated. (2) The first structurally stable particle capable of initiating recrystallization of a phase or the growth of a new phase and possessing an interface with the parent metallic matrix. The term is also applied to a foreign particle that initiates such action.
- **nugget**
  - (1) A small mass of metal, such as gold or silver, found free in nature. (2) The weld metal in a spot, seam, or projection weld.
- ***n*-value**
  - See strain-hardening exponent .
- **O**
- **offhand grinding**
  - Grinding where the operator manually forces the wheel against the work, or vice versa. It often implies casual manipulation of either grinder or work to achieve the desired result. Dimensions and tolerances frequently are not specified, or are only loosely specified; the operator relies mainly on visual inspection to determine how much grinding should be done. Contrast with precision grinding .
- **offset**
  - The distance along the strain coordinate between the initial portion of a stress-strain curve and a parallel line that intersects the stress-strain curve at a value of stress (commonly 0.2%) that is used as a measure of the yield strength. Used for materials that have no obvious yield point.
- **offset yield strength**
  - The stress at which the strain exceeds by a specific amount (the offset) an extension of the initial, approximately linear, proportional portion of the stress-strain curve. It is expressed in force per unit area.
- **oil canning**
  - See canning .
- **oil quenching**
  - Hardening of carbon steel in an oil bath.
- **Olsen ductility test**
  - A cupping test in which a piece of sheet metal, restrained except at the center, is deformed by a standard steel ball until fracture occurs. The height of the cup at the time of fracture is a measure of the ductility.
- **open-back inclinable press**
  - A vertical crank press that can be inclined so that the bed will have an inclination generally varying from 0 to 30°. The formed parts slide off through an opening in the back. It is often called an OBI press.
- **open-die forging**
  - The hot mechanical forming of metals between flat or shaped dies in which metal flow is not completely restricted. Also known as hand or smith forging. See also hand forge (smith forge) .
- **open dies**
  - Dies with flat surfaces that are used for preforming stock or producing hand forgings.
- **open hearth furnace**
  - A reverberatory melting furnace with a shallow hearth and a low roof. The flame passes over the charge on the hearth, causing the charge to be heated both by direct flame and by radiation from the roof and sidewalls of the furnace. See also reverberatory furnace .
- **open rod press**

  - A hydraulic press in which the slide is guided by vertical, cylindrical rods (usually four) that also serve to hold the crown and bed in position.
- **optical emission spectroscopy**
  - Pertaining to emission spectroscopy in the near-ultraviolet, visible, or near-infrared wavelength regions of the electromagnetic spectrum. See also electromagnetic radiation .
- **orange peel**
  - A surface roughening in the form of a pebble-grained pattern that occurs when a metal of unusually coarse grain size is stressed beyond its elastic limit. Also called pebbles and alligator skin.
- **orbital forging**
  - See rotary forging .
- **ordered structure**
  - The crystal structure of a solid solution in which the atoms of different elements seek preferred lattice positions. Contrast with disordered structure .
- **ore**
  - A natural mineral that may be mined and treated for the extraction of any of its components, metallic or otherwise, at a profit.
- **ore dressing**
  - Same as mineral dressing .
- **orientation**
  - Arrangements in space of the axes of the lattice of a crystal with respect to a chosen reference or coordinate system. See also preferred orientation .
- **original crack size (a_o)**
  - The physical crack size at the start of testing.
- **oscillating die press**
  - A small high-speed metal forming press in which the die and punch move horizontally with the strip during the working stroke. Through a reciprocating motion, the die and punch return to their original positions to begin the next stroke.
- **overaging**
  - Aging under conditions of time and temperature greater than those required to obtain maximum change in a certain property, so that the property is altered in the direction of the initial value.
- **overbending**
  - Bending metal through a greater arc than that required in the finished part to compensate for springback.
- **overdraft**
  - A condition wherein a metal curves upward on leaving the rolls because of the higher speed of the lower roll.
- **overhead-drive press**
  - A mechanical press with the driving mechanism mounted in or on the crown or upper parts of the uprights.
- **overheating**
  - Heating a metal or alloy to such a high temperature that its properties are impaired. When the original properties cannot be restored by further heat treating, by mechanical working, or by a combination of working and heat treating, the overheating is known as burning.
- **overlap**
  - In resistance seam welding, the area in a given weld remelted by the succeeding weld.
- **oversize powder**
  - Powder particles larger than the maximum permitted by a particle size specification.
- **overstressing**
  - In fatigue testing, cycling at a stress level higher than that used at the end of the test.
- **oxidation**
  - (1) A reaction in which there is an increase in valence resulting from a loss of electrons. Contrast with reduction . (2) A corrosion reaction in which the corroded metal forms an oxide; usually applied to reaction with a gas containing elemental oxygen, such as air. Elevated temperatures increase the rate of oxidation. (3) A chemical reaction in which one substance is changed to another by oxygen combining with the substance. Much of the dross from holding and melting furnaces is the result of oxidation of the alloy held in the furnace.
- **oxidation losses**

    - Reduction in the amount of metal or alloy through oxidation.
- **oxidative wear**
    - (1) A corrosive wear process in which chemical reaction with oxygen or oxidizing environment predominates. (2) A type of wear resulting from the sliding action between two metallic components that generates oxide films on the metal surfaces. These oxide films prevent the formation of a metallic bond between the sliding surfaces, resulting in fine wear debris and low wear rates.
- **oxidized steel surface**
    - Surface having a thin, tightly adhering oxidized skin (from straw to blue in color), extending in from the edge of a coil or sheet.
- **oxidizing agent**
    - A compound that causes oxidation, thereby itself being reduced.
- **oxidizing atmosphere**
    - A furnace atmosphere with an oversupply of oxygen that tends to oxidize materials placed in it.
- **oxidizing flame**
    - A gas flame produced with excess oxygen in the inner flame that has an oxidizing effect. See also neutral flame and reducing flame .
- **oxyacetylene cutting**
    - An oxyfuel gas cutting process in which the fuel gas is acetylene.
- **oxyacetylene welding**
    - An oxyfuel gas welding process in which the fuel gas is acetylene.
- **oxyfuel gas cutting**
    - Any of a group of processes used to sever metals by means of chemical reaction between hot base metal and a fine stream of oxygen. The necessary metal temperature is maintained by gas flames resulting from combustion of a specific fuel gas such as acetylene, hydrogen, natural gas, propane, propylene, or Mapp gas (stabilized methylacetylene-propadiene).
- **oxyfuel gas welding (OFW)**
    - Any of a group of processes used to fuse metals together by heating them with gas flames resulting from combustion of a specific fuel gas such as acetylene, hydrogen, natural gas, or propane. The process may be used with or without the application of pressure to the joint, and with or without adding any filler metal.
- **oxygas cutting**
    - See preferred term oxygen cutting .
- **oxygen arc cutting**
    - An oxygen cutting process used to sever metals by means of the chemical reaction of oxygen with the base metal at elevated temperatures. The necessary temperature is maintained by an arc between a consumable tubular electrode and the base metal.
- **oxygen cutting**
    - A group of cutting processes used to sever or remove metals by means of the chemical reaction between oxygen and the base metal at elevated temperatures. In the case of oxidation-resistant metals, the reaction is facilitated by the use of a chemical flux or metal powder. See also chemical flux cutting , metal powder cutting , oxyfuel gas cutting , oxygen arc cutting , and oxygen lance cutting .
- **oxygen-free copper**
    - Electrolytic copper free from cuprous oxide, produced without the use of residual metallic or metalloidal deoxidizers.
- **Oxygen gouging**
    - Oxygen cutting in which a bevel or groove is formed.
- **oxygen lance**
    - A length of pipe used to convey oxygen either beneath or on top of the melt in a steelmaking furnace, or to the point of cutting in oxygen lance cutting.
- **oxygen lance cutting**
    - An oxygen cutting process used to sever metals with oxygen supplied through a consumable lance; the preheat to start the cutting is obtained by other means.
- **oxygen probe**
    - An atmosphere-monitoring device that electronically measures the difference between the partial pressure of oxygen in a furnace or furnace supply atmosphere and the external air.
- **P**

- **pack carburizing**
  - A method of surface hardening of steel in which parts are packed in a steel box with a carburizing compound and heated to elevated temperatures. This process has been largely supplanted by gas and liquid carburizing processes.
- **pack nitriding**
  - A method of surface hardening of steel in which parts are packed in a steel box with a nitriding compound and heated to elevated temperatures.
- **pack rolling**
  - Hot rolling a pack of two or more sheets of metal; scale prevents their being welded together.
- **pancake forging**
  - A rough forged shape, usually flat, that can be obtained quickly with minimal tooling. Considerable machining is usually required to attain the finish size.
- **pancake grain structure**
  - A metallic structure in which the lengths and widths of individual grains are large compared to their thicknesses.
- **paramagnetic material**
  - (1) A material whose specific permeability is greater than unity and is practically independent of the magnetizing force. (2) Material with a small positive susceptibility due to the interaction and independent alignment of permanent atomic and electronic magnetic moments with the applied field. Compare with ferromagnetic material .
- **paramagnetism**
  - A property exhibited by substances that, when placed in a magnetic field, are magnetized parallel to the field to an extent proportional to the field (except at very low temperatures or in extremely large magnetic fields). Compare with ferromagnetism .
- **Parkes process**
  - A process used to recover precious metals from lead and based on the principle that if 1 to 2% Zn is stirred into the molten lead, a compound of zinc with gold and silver separates out and can be skimmed off.
- **partial annealing**
  - An imprecise term used to denote a treatment given cold-worked metallic material to reduce its strength to a controlled level or to effect stress relief. To be meaningful, the type of material, the degree of cold work, and the time-temperature schedule must be stated.
- **particle shape**
  - The appearance of a metal particle, such as spherical, rounded, angular, acicular, dendritic, irregular, porous, fragmented, blocky, rod, flake, nodular, or plate.
- **particle size**
  - The controlling lineal dimension of an individual particle as determined by analysis with screens or other suitable instruments. See also sieve analysis and sieve classification .
- **particle size distribution**
  - The percentage, by weight or by number, of each fraction into which a powder or sand sample has been classified with respect to sieve number or particle size.
- **particle sizing**
  - Segregation of granular material into specified particle size ranges.
- **parting**
  - (1) In the recovery of precious metals, the separation of silver from gold. (2) The zone of separation between cope and drag portions of the mold or flask in sand casting. (3) A composition sometimes used in sand molding to facilitate the removal of the pattern. (4) Cutting simultaneously along two parallel lines or along two lines that balance each other in side thrust. (5) A shearing operation used to produce two or more parts from a stamping.
- **parting compound**
  - A material dusted or sprayed on foundry (casting) patterns to prevent adherence of sand and to promote easy separation of cope and drag parting surfaces when the cope is lifted from the drag.
- **parting line**
  - (1) The intersection of the parting plane of a casting or plastic mold or the parting plane between forging dies with the mold or die cavity. (2) A raised line or projection on the surface of a casting, plastic part, or forging that corresponds to said intersection.
- **parting plane**

  - (1) In forging, the dividing line between dies. (2) In casting, the dividing line between mold halves.
- **parting sand**
  - In foundry practice, a fine sand for dusting on sand mold surfaces that are to be separated.
- **pass**
  - (1) A single transfer of metal through a stand of rolls. (2) The open space between two grooved rolls through which metal is processed. (3) The weld metal deposited in one trip along the axis of a weld. See also weld pass .
- **passivation**
  - (1) A reduction of the anodic reaction rate of an electrode involved in corrosion. (2) The process in metal corrosion by which metals become passive. (3) The changing of a chemically active surface of a metal to a much less reactive state. Contrast with activation .
- **passive**
  - (1) A metal corroding under the control of a surface reaction product. (2) The state of the metal surface characterized by low corrosion rates in a potential region that is strongly oxidizing for the metal.
- **passive-active cell**
  - A corrosion cell in which the anode is a metal in the active state and the cathode is the same metal in the passive state.
- **passivity**
  - A condition in which a piece of metal, because of an impervious covering of oxide or other compound, has a potential much more positive than that of the metal in the active state.
- **patenting**
  - In wiremaking, a heat treatment applied to medium- or high-carbon steel before drawing of wire or between drafts. This process consists of heating to a temperature above the transformation range and then cooling to a temperature below Ae_1 in air or in a bath of molten lead or salt.
- **patent leveling**
  - Same as stretcher leveling .
- **patina**
  - The coating, usually green, that forms on the surface of metals such as copper and copper alloys exposed to the atmosphere. Also used to describe the appearance of a weathered surface of any metal.
- **pattern**
  - (1) A form of wood, metal, or other material around which molding material is placed to make a mold for casting metals. (2) A form of wax- or plastic-base material around which refractory material is placed to make a mold for casting metals. (3) A full-scale reproduction of a part used as a guide in cutting.
- **pearlite**
  - A metastable lamellar aggregate of ferrite and cementite resulting from the transformation of austenite at temperatures above the bainite range.
- **pearlitic malleable**
  - See malleable iron .
- **pearlitic structure**
  - A microstructure resembling that of the pearlite constituent in steel. Therefore, it is a lamellar structure of varying degrees of coarseness.
- **peeling**
  - The detaching of one layer of a coating from another, or from the substrate, because of poor adherence.
- **peel test**
  - A destructive method of inspection that mechanically separates a lap joint by peeling.
- **peening**
  - Mechanical working of metal by hammer blows or shot impingement.
- **penetrant**
  - A liquid with low surface tension used in liquid penetrant inspection to flow into surface openings of parts being inspected.
- **penetrant inspection**
  - See preferred term liquid penetrant inspection .
- **penetration**

  - (1) In founding, an imperfection on a casting surface caused by metal running into voids between sand grains; usually referred to as metal penetration . (2) In welding, the distance from the original surface of the base metal to that point at which fusion ceased.
- **penetration hardness**
  - Same as indentation hardness .
- **percussion welding**
  - A resistance welding process that produces coalescence of abutting surfaces using heat from an arc produced by a rapid discharge of electrical energy. Pressure is applied percussively during or immediately following the electrical discharge.
- **perforating**
  - The punching of many holes, usually identical and arranged in a regular pattern, in a sheet, workpiece blank, or previously formed part. The holes are usually round, but may be any shape. The operation is also called multiple punching. See also piercing .
- **peripheral milling**
  - Milling a surface parallel to the axis of the cutter.
- **peritectic**
  - An isothermal reversible reaction in metals in which a liquid phase reacts with a solid phase to produce a single (and different) solid phase on cooling.
- **peritectoid**
  - An isothermal reversible reaction in which a solid phase reacts with a second solid phase to produce a single (and different) solid phase on cooling.
- **permanent magnet material**
  - A ferromagnetic alloy capable of being magnetized permanently because of its ability to retain induced magnetization and magnetic poles after removal of externally applied fields; an alloy with high coercive force. The name is based on the fact that the quality of the early permanent magnets was related to their hardness.
- **permanent mold**
  - A metal, graphite, or ceramic mold (other than an ingot mold) of two or more parts that is used repeatedly for the production of many castings of the same form. Liquid metal is usually poured in by gravity.
- **permanent set**
  - The deformation remaining after a specimen has been stressed a prescribed amount in tension, compression, or shear for a specified time period and released for a specified time period. For creep tests, the residual unrecoverable deformation after the load causing the creep has been removed for a substantial and specified period of time. Also, the increase in length, expressed as a percentage of the original length, by which an elastic material fails to return to its original length after being stressed for a standard period of time.
- **permeability**
  - (1) The passage or diffusion (or rate of passage) of a gas, vapor, liquid, or solid through a material (often porous) without physically or chemically affecting it; the measure of fluid flow (gas or liquid) through a material. (2) A general term used to express various relationships between magnetic induction and magnetizing force. These relationships are either "absolute permeability," which is a change in magnetic induction divided by the corresponding change in magnetizing force, or "specific (relative) permeability," the ratio of the absolute permeability to the permeability of free space. (3) In metal casting, the characteristics of molding materials that permit gases to pass through them. "Permeability number" is determined by a standard test.
- **pewter**
  - A tin-base white metal containing antimony and copper. Originally, pewter was defined as an alloy of tin and lead, but to avoid toxicity and dullness of finish, lead is excluded from modern pewter. These modern compositions contain 1 to 8% Sb and 0.25 to 3% Cu.
- **pH**
  - The negative logarithm of the hydrogen-ion activity; it denotes the degree of acidity or basicity of a solution. At 25 °C (77 °F), 7.0 is the neutral value. Decreasing values below 7.0 indicates increasing acidity; increasing values above 7.0, increasing basicity. The pH values range from 0 to 14.
- **phase**
  - A physically homogeneous and distinct portion of a material system.
- **phase change**

  - The transition from one physical state to another, such as gas to liquid, liquid to solid, gas to solid, or vice versa.
- **phase diagram**
  - A graphical representation of the temperature and composition limits of phase fields in an alloy or ceramic system as they actually exist under the specific conditions of heating or cooling. A phase diagram may be an equilibrium diagram, an approximation to an equilibrium diagram, or a representation of metastable conditions or phases. Synonymous with constitution diagram. Compare with equilibrium diagram .
- **phase rule**
  - The maximum number of phases (P) that may coexist at equilibrium is two, plus the number of components (C) in the mixture, minus the number of degrees of freedom (F): $P + F = C + 2$.
- **phosphating**
  - Forming an adherent phosphate coating on a metal by immersion in a suitable aqueous phosphate solution. Also called phosphatizing. See also conversion coating .
- **phosphorized copper**
  - General term applied to copper deoxidized with phosphorus. The most commonly used deoxidized copper.
- **photoelasticity**
  - An optical method for evaluating the magnitude and distribution of stresses, using a transparent model of a part, or a thick film of photoelastic material bonded to a real part.
- **photomacrograph**
  - A macrograph produced by photographic means.
- **photomicrograph**
  - A micrograph produced by photographic means.
- **physical crack size (a_p)**
  - In fracture mechanics, the distance from a reference plane to the observed crack front. This distance may represent an average of several measurements along the crack front. The reference plane depends on the specimen form, and it is normally taken to be either the boundary or a plane containing either the load line or the centerline of a specimen or plate.
- **physical metallurgy**
  - The science and technology dealing with the properties of metals and alloys, and of the effects of composition, processing, and environment on those properties.
- **physical properties**
  - Properties of a material that are relatively insensitive to structure and can be measured without the application of force; for example, density, electrical conductivity, coefficient of thermal expansion, magnetic permeability, and lattice parameter. Does not include chemical reactivity. Compare with mechanical properties .
- **physical testing**
  - Methods used to determine the entire range of the material's physical properties of a material. In addition to density and thermal, electrical, and magnetic properties, physical testing methods may be used to assess simple fundamental physical properties such as color, crystalline form, and melting point.
- **physical vapor deposition (PVD)**
  - A coating process whereby the deposition species are transferred and deposited in the form of individual atoms or molecules. The most common PVD methods are sputtering and evaporation. Sputtering, which is the principal PVD process, involves the transport of a material from a source (target) to a substrate by means of the bombardment of the target by gas ions that have been accelerated by a high voltage. Evaporation, which was the first PVD process used, involves the transfer of material to form a coating by physical means alone, essentially vaporization. Physical vapor deposition coatings are used to improve the wear, friction, and hardness properties of cutting tools and as corrosion-resistant coatings.
- **pickle liquor**
  - A spent acid-pickling bath.
- **pickle stain**
  - Discoloration of metal due to chemical cleaning without adequate washing and drying.
- **pickling**

  - The chemical removal of surface oxides (scale) and other contaminants such as dirt from iron and steel by immersion in an aqueous acid solution. The most common pickling solutions are sulfuric and hydrochloric acids.
- **pickoff**
  - An automatic device for removing a finished part from the press die after it has been stripped.
- **pickup**
  - (1) Transfer of metal from tools to part or from part to tools during a forming operation. (2) Small particles of oxidized metal adhering to the surface of a mill product.
- **Pidgeon process**
  - A process for production of magnesium by reduction of magnesium oxide with ferrosilicon.
- **piercing**
  - The general term for cutting (shearing or punching) openings, such as holes and slots, in sheet material, plate, or parts. This operation is similar to blanking; the difference is that the slug or pierce produced by piercing is scrap, while the blank produced by blanking is the useful part.
- **piezoelectric effect**
  - The reversible interaction, exhibited by some crystalline materials, between an elastic strain and an electric field. The direction of the strain depends on the polarity of the field or vice versa. Compare with electrostrictive effect .
- **pig**
  - A metal casting used in remelting.
- **pig iron**
  - (1) High-carbon iron made by reduction of iron ore in the blast furnace. (2) Cast iron in the form of pigs.
- **Pilger tube-reducing process**
  - See tube reducing .
- **pin (for bend testing)**
  - The plunger or tool used in making semiguided, guided, or wraparound bend tests to apply the bending force to the inside surface of the bend. In free bends or semiguided bends to an angle of 180°, a shim or block of the proper thickness may be placed between the legs of the specimen as bending is completed. This shim or block is also referred to as a pin or mandrel. See also mandrel .
- **pinchers**
  - Surface disturbances on metal sheet or strip that result from rolling processes and that ordinarily appear as fernlike ripples running diagonally to the direction of rolling.
- **pinch pass**
  - A pass of sheet metal through rolls to effect a very small reduction in thickness.
- **pinch trimming**
  - The trimming of the edge of a tubular metal part or shell by pushing or pinching the flange or lip over the cutting edge of a stationary punch or over the cutting edge of a draw punch.
- **pin expansion test**
  - A test for determining the ability of a tube to be expanded or for revealing the presence of cracks or other longitudinal weaknesses, made by forcing a tapered pin into the open end of the tube.
- **pinhole porosity**
  - Porosity consisting of numerous small gas holes (pinholes) distributed throughout the metal; found in weld metal, castings, and electrodeposited metal.
- **Piobert lines**
  - See Lüders lines .
- **pipe**
  - (1) The central cavity formed by contraction in metal, especially ingots, during solidification. (2) An imperfection in wrought or cast products resulting from such a cavity. (3) A tubular metal product, cast or wrought. See also extrusion pipe .
- **pipe tap**
  - A tap for making internal pipe threads within pipe fittings or holes.
- **pipe threads**
  - Internal or external machine threads, usually tapered, of a design intended for making pressure-tight mechanical joints in piping systems.
- **pit**

    - A small, regular or irregular crater in the surface of a material created by exposure to the environment, for example, corrosion, wear, or thermal cycling. See also pitting .
- **pitting**
    - (1) Forming small sharp cavities in a surface by corrosion, wear, or other mechanically assisted degradation. (2) Localized corrosion of a metal surface, confined to a point or small area, that takes the form of cavities.
- **plane strain**
    - The stress condition in linear elastic fracture mechanics in which there is zero strain in a direction normal to both the axis of applied tensile stress and the direction of crack growth (that is, parallel to the crack front); most nearly achieved in loading thick plates along a direction parallel to the plate surface. Under plane-strain conditions, the plane of fracture instability is normal to the axis of the principal tensile stress.
- **plane-strain fracture toughness (K_{Ic})**
    - The crack extension resistance under conditions of crack-tip plane strain. See also stress-intensity factor .
- **plane stress**
    - The stress condition in linear elastic fracture mechanics in which the stress in the thickness direction is zero; most nearly achieved in loading very thin sheet along a direction parallel to the surface of the sheet. Under plane-stress conditions, the plane of fracture instability is inclined 45° to the axis of the principal tensile stress.
- **plane-stress fracture toughness (K_c)**
    - In linear elastic fracture mechanics, the value of the crack-extension resistance at the instability condition determined from the tangency between the R-curve and the critical crack-extension force curve of the specimen. See also stress-intensity factor .
- **planimetric method**
    - A method of measuring grain size in which the grains within a definite area are counted.
- **planing**
    - Producing flat surfaces by linear reciprocal motion of work and the table to which it is attached, relative to a stationary single-point cutting tool.
- **planishing**
    - Producing a smooth finish on metal by a rapid succession of blows delivered by highly polished dies or by a hammer designed for the purpose, or by rolling in a planishing mill.
- **plasma arc cutting**
    - An arc cutting process that severs metals by melting a localized area with heat from a constricted arc and removing the molten metal with a high-velocity jet of hot, ionized gas issuing from the plasma torch.
- **plasma arc welding (PAW)**
    - An arc welding process that produces coalescence of metals by heating them with a constricted arc between an electrode and the workpiece (transferred arc) or the electrode and the constricting nozzle (nontransferred arc). Shielding is obtained from hot, ionized gas issuing from an orifice surrounding the electrode and may be supplemented by an auxiliary source of shielding gas, which may be an inert gas or a mixture of gases. Pressure may or may not be used, and filler metal may or may not be supplied.
- **plasma-assisted chemical vapor deposition**
    - A chemical vapor deposition process that uses low-pressure glow-discharge plasmas to promote the chemical deposition reactions. Also called plasma-enhanced chemical vapor deposition.
- **plasma carburizing**
    - Same as ion carburizing .
- **plasma nitriding**
    - Same as ion nitriding .
- **plasma spraying**
    - A thermal spraying process in which a nontransferred arc of a plasma torch is utilized to create a gas plasma that acts as the source of heat for melting and propelling the surfacing material to the substrate.
- **plaster molding**
    - Molding in which a gypsum-bonded aggregate flour in the form of a water slurry is poured over a pattern, permitted to harden, and, after removal of the pattern, thoroughly dried. This technique is used to make smooth nonferrous castings of accurate size.

- **plastic deformation**
  - The permanent (inelastic) distortion of materials under applied stresses that strain the material beyond its elastic limit.
- **plastic flow**
  - The phenomenon that takes place when metals are stretched or compressed permanently without rupture.
- **plasticity**
  - The property of a material that allows it to be repeatedly deformed without rupture when acted upon by a force sufficient to cause deformation and that allows it to retain its shape after the applied force has been removed.
- **plastic-strain ratio (*r*-value)**
  - In formability testing of metals, the ratio of the true width strain to the true thickness strain in a sheet tensile test, $r = \varepsilon_w\varepsilon_t$. A formability parameter that relates to drawing, it is also known as the anisotropy factor. A high *r*-value indicates a material with good drawing properties.
- **plate**
  - A flat-rolled metal product of some minimum thickness and width arbitrarily dependent on the type of metal. Plate thicknesses commonly range from 6 to 300 mm (0.25 to 12 in.); widths from 200 to 2000 mm (8 to 80 in.).
- **plate martensite**
  - Martensite formed partly in steel containing more than approximately 0.5% C and solely in steel containing more than approximately 1.0% C that appears as lenticular-shape plates (crystals).
- **platen**
  - (1) The sliding member, slide, or ram of a metal forming press. (2) A part of a resistance welding, mechanical testing, or other machine with a flat surface to which dies, fixtures, backups, or electrode holders are attached and that transmits pressure or force.
- **plating**
  - Forming an adherent layer of metal on an object; often used as a shop term for electroplating. See also electrodeposition and electroless plating .
- **plating rack**
  - A fixture used to hold work and conduct current to it during electroplating.
- **plug**
  - (1) A rod or mandrel over which a pierced tube is forced. (2) A rod or mandrel that fills a tube as it is drawn through a die. (3) A punch or mandrel over which a cup is drawn. (4) A protruding portion of a die impression for forming a corresponding recess in the forging. (5) A false bottom in a die.
- **plug tap**
  - A tap with chamfer extending from three to five threads.
- **plug weld**
  - A weld made in a circular hole in one member of a joint, fusing that member to another member.
- **plumbage**
  - A special quality of powdered graphite used to coat molds and, in a mixture of clay, to make crucibles.
- **plunge grinding**
  - Grinding wherein the only relative motion of the wheel is radially toward the work.
- **plus mesh**
  - The powder sample retained on a screen of stated size, identified by the retaining mesh number. See also sieve analysis and sieve classification .
- **plus sieve**
  - The portion of a sample of a granular substance (such as metal powder) retained on a standard sieve of specified number. Contrast with minus sieve . See also sieve analysis and sieve classification .
- **plymetal**
  - Sheet consisting of bonded layers of dissimilar metals.
- **P/M**
  - The acronym for powder metallurgy .
- **pneumatic press**
  - A press that uses air or a gas to deliver the pressure to the upper and lower rams.
- **point angle**

  - In general, the angle at the point of a cutting tool. Most commonly, the included angle at the point of a twist drill, the general-purpose angle being 118°.
- **Poisson's ratio (ν)**
  - The absolute value of the ratio of transverse (lateral) strain to the corresponding axial strain resulting from uniformly distributed axial stress below the proportional limit of the material.
- **polarity (welding)**
  - See direct current electrode negative and direct current electrode positive .
- **polarization**
  - (1) The change from the open-circuit electrode potential as the result of the passage of current. (2) A change in the potential of an electrode during electrolysis, such that the potential of an anode becomes more noble, and that of a cathode more active, than their respective reversible potentials. Often accomplished by formation of a film on the electrode surface.
- **polarization curve**
  - A plot of current density versus electrode potential for a specific electrode-electrolyte combination.
- **pole**
  - (1) A means of designating the orientation of a crystal plane by stereographically plotting its normal. For example, the north pole defines the equatorial plane. (2) Either of the two regions of a permanent magnet or electromagnet where most of the lines of induction enter or leave.
- **pole figure**
  - A stereoscopic projection of a polycrystalline aggregate showing the distribution of poles, or plane normals, of a specific crystalline plane, using specimen axes as reference axes. Pole figures are used to characterize preferred orientation in polycrystalline materials.
- **polishing**
  - (1) Smoothing metal surfaces, often to a high luster, by rubbing the surface with a fine abrasive, usually contained in a cloth or other soft lap. Results in microscopic flow of some surface metal together with actual removal of a small amount of surface metal. (2) Removal of material by the action of abrasive grains carried to the work by a flexible support, generally either a wheel or a coated abrasive belt. (3) A mechanical, chemical, or electrolytic process or combination thereof used to prepare a smooth, reflective surface suitable for microstructural examination that is free of artifacts or damage introduced during prior sectioning or grinding. See also electrolytic polishing and electropolishing .
- **polycrystalline**
  - Pertaining to a solid comprised of many crystals or crystallites, intimately bonded together. May be homogeneous (one substance) or heterogeneous (two or more crystal types or compositions).
- **polymorphism**
  - A general term for the ability of a solid to exist in more than one form. In metals, alloys, and similar substances, this usually means the ability to exist in two or more crystal structures, or in an amorphous state and at least one crystal structure. See also allotropy , enantiotropy , and monotropism .
- **pop-off**
  - Loss of small portions of a porcelain enamel coating. The usual cause is outgassing of hydrogen or other gases from the substrate during firing, but pop-off may also occur because of oxide particles or other debris on the surface of the substrate. Usually, the pits are minute and cone shaped, but when pop-off is the result of severe fishscale the pits may be much larger and irregular.
- **porcelain enamel**
  - A substantially vitreous or glassy, inorganic coating (borosilicate glass) bonded to metal by fusion at a temperature above 425 °C (800 °F). Porcelain enamels are applied primarily to components made of sheet iron or steel, cast iron, aluminum, or aluminum-coated steels.
- **pore**
  - (1) A small opening, void, interstice, or channel within a consolidated solid mass or agglomerate, usually larger than atomic or molecular dimensions. (2) A minute cavity in a powder metallurgy compact, sometimes added intentionally. (3) A minute perforation in an electroplated coating.
- **porosity**
  - (1) Fine holes or pores within a solid; the amount of these pores is expressed as a percentage of the total volume of the solid. (2) Cavity-type discontinuities in weldments formed by gas

entrapment during solidification. (3) A characteristic of being porous, with voids or pores resulting from trapped air or shrinkage in a casting. See also gas porosity and pinhole porosity .

- **postheating**
  - Heating weldments immediately after welding, for tempering, for stress relieving, or for providing a controlled rate of cooling to prevent formation of a hard or brittle structure. See also postweld heat treatment .
- **postweld heat treatment**
  - Any heat treatment that follows the welding operation.
- **pot**
  - (1) A vessel for holding molten metal. (2) The electrolytic reduction cell used to make such metals as aluminum from a fused electrolyte.
- **pot annealing**
  - Same as box annealing .
- **potential**
  - (1) Any of various functions from which intensity or velocity at any point in a field may be calculated. (2) The driving influence of an electrochemical reaction .
- **poultice corrosion**
  - A term used in the automotive industry to describe the corrosion of vehicle body parts due to the collection of road salts and debris on ledges and in pockets that are kept moist by weather and washing. Also called deposit corrosion or attack.
- **pouring**
  - The transfer of molten metal from furnace to ladle, ladle to ladle, or ladle into molds.
- **pouring basin**
  - In metal casting, a basin on top of a mold that receives the molten metal before it enters the sprue or downgate.
- **powder**
  - An aggregate of discrete particles that are usually in the size range of 1 to 1000 μm.
- **powder cutting**
  - See preferred terms chemical flux cutting and metal powder cutting .
- **powder flame spraying**
  - A thermal spraying process variation in which the material to be sprayed is in powder form.
- **powder forging**
  - The plastic deformation of a powder metallurgy compact or preform into a fully dense finished shape by using compressive force; usually done hot and within closed dies.
- **powder lubricant**
  - In powder metallurgy, an agent or component incorporated into a mixture to facilitate compacting and ejecting of the compact from its mold.
- **powder metallurgy (P/M)**
  - The technology and art of producing metal powders and utilizing metal powders for production of massive materials and shaped objects.
- **powder metallurgy forging**
  - See powder forging .
- **powder metallurgy part**
  - A shaped object that has been formed from metal powders and sintered by heating below the melting point of the major constituent. A structural or mechanical component made by the powder metallurgy process.
- **prealloyed powder**
  - A metallic powder composed of two or more elements that are alloyed in the powder manufacturing process and in which the particles are of the same nominal composition throughout.
- **precious metals**
  - Relatively scarce, highly corrosion resistant, valuable metals found in periods 5 and 6 (groups VIII and Ib) of the periodic table. They include ruthenium, rhodium, palladium, silver, asmium, iridium, platinum, and gold. See also noble metal .
- **precipitation**
  - In metals, the separation of a new phase from solid or liquid solution, usually with changing conditions of temperature, pressure, or both.

- **precipitation hardening**
  - Hardening in metals caused by the precipitation of a constituent from a supersaturated solid solution. See also age hardening and aging .
- **precipitation heat treatment**
  - Artificial aging of metals in which a constituent precipitates from a supersaturated solid solution.
- **precision casting**
  - A metal casting of reproducible, accurate dimensions, regardless of how it is made. Often used interchangeably with investment casting .
- **precision forging**
  - A forging produced to closer tolerances than normally considered standard by the industry. With precision forging, a net shape, or at least a near-net shape, can be produced in the as-forged condition. See also net shape .
- **precision grinding**
  - Machine grinding to specified dimensions and low tolerances.
- **precoat**
  - (1) In investment casting, a special refractory slurry applied to a wax or plastic expendable pattern to form a thin coating that serves as a desirable base for application of the main slurry. See also investment casting . (2) To make the thin coating. (3) The thin coating itself.
- **precoated metal products**
  - Mill products that have a metallic, organic, or conversion coating applied to their surfaces before they are fabricated into parts.
- **precracked specimen**
  - A mechanical test specimen that is notched and subjected to alternating stresses until a crack has developed at the root of the notch.
- **preferred orientation**
  - A condition of a polycrystalline aggregate in which the crystal orientations are not random, but rather exhibit a tendency for alignment with a specific direction in the bulk material, commonly related to the direction of working. See also texture .
- **preforming**
  - (1) The initial pressing of a metal powder to form a compact that is to be subjected to a subsequent pressing operation other than coining or sizing. (2) Preliminary forming operations, especially for impression-die forging.
- **preheating**
  - (1) Heating before some further thermal or mechanical treatment. For tool steel, heating to an intermediate temperature immediately before final austenitizing. For some nonferrous alloys, heating to a high temperature for a long time, in order to homogenize the structure before working. (2) In welding and related processes, heating to an intermediate temperature for a short time immediately before welding, brazing, soldering, cutting, or thermal spraying. (3) In powder metallurgy, an early stage in the sintering procedure when, in a continuous furnace, lubricant or binder burnoff occurs without atmosphere protection prior to actual sintering in the protective atmosphere of the high heat chamber.
- **presintering**
  - Heating a powder metallurgy compact to a temperature below the final sintering temperature, usually to increase the ease of handling or shaping of a compact or to remove a lubricant or binder (burnoff) prior to sintering.
- **press**
  - A machine tool having a stationary bed and a slide or ram that has reciprocating motion at right angles to the bed surface, the slide being guided in the frame of the machine. See also hydraulic press , mechanical press , and slide .
- **press brake**
  - An open-frame single-action press used to bend, blank, corrugate, curl, notch, perforate, pierce, or punch sheet metal or plate.
- **press-brake forming**
  - A metalforming process in which the workpiece is placed over an open die and pressed down into the die by a punch that is actuated by the ram portion of a press brake. The process is most widely used for the forming of relatively long, narrow parts that are not adaptable to press forming and for applications in which production quantities are too small to warrant the tooling cost for contour roll forming.

- **pressed density**
    - The weight per unit volume of an unsintered compact. Same as green density .
- **press forming**
    - Any sheet metalforming operation performed with tooling by means of a mechanical or hydraulic press.
- **pressing area**
    - The clear distance (left to right) between housings, stops, gibs, gibways, or shoulders of strain rods, multiplied by the total distance from front to back on the bed of a metalforming press. Sometimes called working area.
- **pressing crack**
    - A rupture in a green powder metallurgy compact that develops during ejection of the compact from the die. Sometimes referred to as a slip crack.
- **press quenching**
    - A quench in which hot dies are pressed and aligned with a part before the quenching process begins. Then the part is placed in contact with a quenching medium in a controlled manner. This process avoids part distortion.
- **pressure casting**
    - (1) Making castings with pressure on the molten or plastic metal, as in die casting, centrifugal casting, cold chamber pressure casting, and squeeze casting. (2) A casting made with pressure applied to the molten or plastic metal.
- **pressure-controlled welding**
    - A resistance welding process variation in which a number of spot or projection welds are made with several electrodes functioning progressively under the control of a pressure-sequencing device.
- **pressure gas welding**
    - An oxyfuel gas welding process that produces coalescence simultaneously over the entire area of abutting surfaces by heating them with gas flames obtained from combustion of a fuel gas with oxygen and by application of pressure, without the use of filler metal.
- **pressure sintering**
    - A hot-pressing technique that usually employs low loads, high sintering temperatures, continuous or discontinuous sintering, and simple molds to contain the powder. Although the terms pressure sintering and hot pressing are used interchangeably, distinct differences exist between the two processes. In pressure sintering, the emphasis is on thermal processing; in hot pressing, applied pressure is the main process variable.
- **pressure welding**
    - See preferred terms cold welding , diffusion welding , forge welding , hot pressure welding , pressure-controlled welding , pressure gas welding , and solid-state welding .
- **primary creep**
    - The first, or initial, stage of creep, or time-dependent deformation.
- **primary crystals**
    - The first type of crystals that separate from a melt during solidification.
- **primary metal**
    - Metal extracted from minerals and free of reclaimed metal scrap. Compare with native metal .
- **primary mill**
    - A mill for rolling ingots or the rolled products of ingots to blooms, billets, or slabs. This type of mill is often called a blooming mill and sometimes called a cogging mill.
- **principal stress (normal)**
    - The maximum or minimum value of the normal stress at a point in a plane considered with respect to all possible orientations of the considered plane. On such principal planes the shear stress is zero. There are three principal stresses on three mutually perpendicular planes. The state of stress at a point may be (1) uniaxial, a state of stress in which two of the three principal stresses are zero, (2) biaxial, a state of stress in which only one of the three principal stresses is zero, and (3) triaxial, a state of stress in which none of the principal stresses is zero. Multiaxial stress refers to either biaxial or triaxial stress.
- **process annealing**
    - A heat treatment used to soften metal for further cold working. In ferrous sheet and wire industries, heating to a temperature close to but below the lower limit of the transformation range and subsequently cooling for working. In the nonferrous industries, heating above the

recrystallization temperatures at a time and temperature sufficient to permit the desired subsequent cold working.

- **process metallurgy**
  - The science and technology of winning metals from their ores and purifying metals; sometimes referred to as chemical metallurgy. Its two chief branches are extractive metallurgy and refining.
- **proeutectoid phase**
  - Particles of a phase in ferrous alloys that precipitate during cooling after austenitizing but before the eutectoid transformation takes place. See also eutectoid .
- **profiling**
  - Any operation that produces an irregular contour on a workpiece, for which a tracer or template-controlled duplicating equipment usually is employed.
- **progressive aging**
  - Aging by increasing the temperature in steps or continuously during the aging cycle. See also aging and compare with interrupted aging and step aging .
- **progressive die**
  - A die with two or more stations arranged in line for performing two or more operations on a part; one operation is usually performed at each station.
- **progressive forming**
  - Sequential forming at consecutive stations with a single die or separate dies.
- **projection welding**
  - A resistance welding process that produces coalescence of metals with the heat obtained from resistance to electric current through the work parts held together under pressure by electrodes. The resulting welds are localized at predetermined points by projections, embossments, or intersections.
- **proof**
  - (1) To test a component or system at its peak operating load or pressure. (2) Any reproduction of a die impression in any material; often a lead or plaster cast. See also die proof .
- **proof load**
  - A predetermined load, generally some multiple of the service load, to which a specimen or structure is submitted before acceptance for use.
- **proof stress**
  - (1) A specified stress to be applied to a member or structure to indicate its ability to withstand service loads. (2) The stress that will cause a specified small permanent set in a material.
- **proportional limit**
  - The greatest stress a material is capable of developing without a deviation from straight-line proportionality between stress and strain. See also elastic limit and Hooke's law .
- **protective atmosphere**
  - (1) A gas or vacuum envelope surrounding the part to be brazed, welded, or thermal sprayed, with the gas composition controlled with respect to chemical composition, dew point, pressure, flow rate, and so forth. Examples are inert gases, combusted fuel gases, hydrogen, and vacuum. (2) The atmosphere in a heat treating or sintering furnace designed to protect the parts or compacts from oxidation, nitridation, or other contamination from the environment.
- **pseudobinary system**
  - (1) A three-component or ternary alloy system in which an intermediate phase acts as a component. (2) A vertical section through a ternary diagram.
- **puckering**
  - Wrinkling or buckling in a drawn shell in an area originally inside the draw ring.
- **pull cracks**
  - In a casting, cracks that are caused by residual stresses produced during cooling and that result from the shape of the object.
- **pulverization**
  - The process of reducing metal powder particle sizes by mechanical means; also called comminution or mechanical disintegration.
- **punch**
  - (1) The male part of a die--as distinguished from the female part, which is called the die. The punch is usually the upper member of the complete die assembly and is mounted on the slide or in a die set for alignment (except in the inverted die). (2) In double-action draw dies, the punch is the inner portion of the upper die, which is mounted on the plunger (inner slide) and does the

  drawing. (3) The act of piercing or punching a hole. Also referred to as punching . (4) The movable tool that forces material into the die in powder molding and most metalforming operations. (5) The movable die in a trimming press or a forging machine. (6) The tool that forces the stock through the die in rod and tube extrusion and forms the internal surface in can or cup extrusion.
- **punching**
  - (1) The die shearing of a closed contour in which the sheared out sheet metal part is scrap. (2) Producing a hole by die shearing, in which the shape of the hole is controlled by the shape of the punch and its mating die. Multiple punching of small holes is called perforating . See also piercing .
- **punch press**
  - (1) In general, any mechanical press. (2) In particular, an endwheel gap-frame press with a fixed bed, used in piercing.
- **punch radius**
  - The radius on the end of the punch that first contacts the work, sometimes called nose radius .
- **push bench**
  - Equipment used for drawing moderately heavy-gage tubes by cupping sheet metal and forcing it through a die by pressure exerted against the inside bottom of the cup.
- **pusher furnace**
  - A type of continuous furnace in which parts to be heated are periodically charged into the furnace in containers, which are pushed along the hearth against a line of previously charged containers thus advancing the containers toward the discharge end of the furnace, where they are removed.
- **push welding**
  - Spot or projection welding in which the force is applied manually to one electrode, and the work or backing plate takes the place of the other electrode.
- **pyramidal plane**
  - In noncubic crystals, any plane that intersects all three axes.
- **pyrometallurgy**
  - High-temperature winning or refining of metals.
- **pyrometer**
  - A device for measuring temperatures above the range of liquid thermometers.
- **pyrophoric powder**
  - A powder whose particles self-ignite and burn when exposed to oxygen or air.
- **Q**
- **quality**
  - (1) The totality of features and characteristics of a product or service that bear on its ability to satisfy a given need (fitness-for-use concept of quality). (2) Degree of excellence of a product or service (comparative concept). Often determined subjectively by comparison against an ideal standard or against similar products or services available from other sources. (3) A quantitative evaluation of the features and characteristics of a product or service (quantitative concept).
- **quantitative metallography**
  - Determination of specific characteristics of a microstructure by quantitative measurements on micrographs or metallographic images. Quantities so measured include volume concentration of phases, grain size, particle size, mean free path between like particles or secondary phases, and surface-area-to-volume ratio of microconstituents, particles, or grains.
- **quarter hard**
  - A temper of nonferrous alloys and some ferrous alloys characterized by tensile strength about midway between that of dead soft and half hard tempers.
- **quasi-binary system**
  - In a ternary or higher-order system, a linear composition series between two substances each of which exhibits congruent melting, wherein all equilibria, at all temperatures or pressures, involve only phases having compositions occurring in the linear series, so that the series may be represented as a binary on a phase diagram.
- **quasi-cleavage fracture**
  - A fracture mode that combines the characteristics of cleavage fracture and dimple fracture. An intermediate type of fracture found in certain high-strength metals.
- **quench-age embrittlement**

  - Embrittlement of low-carbon steels resulting from precipitation of solute carbon at existing dislocations and from precipitation hardening of the steel caused by differences in the solid solubility of carbon in ferrite at different temperatures. Quench-age embrittlement usually is caused by rapid cooling of the steel from temperatures slightly below Ac_1 (the temperature at which austenite begins to form), and can be minimized by quenching from lower temperatures.
- **quench aging**
  - Aging induced by rapid cooling after solution heat treatment.
- **quench annealing**
  - Annealing an austenitic ferrous alloy by solution heat treatment followed by rapid quenching.
- **quench cracking**
  - Fracture of a metal during quenching from elevated temperature. Most frequently observed in hardened carbon steel, alloy steel, or tool steel parts of high hardness and low toughness. Cracks often emanate from fillets, holes, corners, or other stress raisers and result from high stresses due to the volume changes accompanying transformation to martensite.
- **quench hardening**
  - (1) Hardening suitable α-β alloys (most often certain copper to titanium alloys) by solution treating and quenching to develop a martensitic-like structure. (2) In ferrous alloys, hardening by austenitizing and then cooling at a rate such that a substantial amount of austenite transforms to martensite.
- **quenching**
  - Rapid cooling of metals (often steels) from a suitable elevated temperature. This generally is accomplished by immersion in water, oil, polymer solution, or salt, although forced air is sometimes used. See also brine quenching , caustic quenching , direct quenching , fog quenching , forced-air quenching , hot quenching , intense quenching , interrupted quenching , oil quenching , press quenching , selective quenching , spray quenching , time quenching , and water quenching .
- **quenching crack**
  - A crack formed in a metal as a result of thermal stresses produced by rapid cooling from a high temperature.
- **quenching oil**
  - Oil used for quenching metals during a heat treating operation.
- **R**
- **rabbit ear**
  - Recess in the corner of a metalforming die to allow for wrinkling or folding of the blank.
- **racking**
  - A term used to describe the placing of metal parts to be heat treated on a rack or tray. This is done to keep parts in a proper position to avoid heat-related distortions and to keep the parts separated.
- **radial draw forming**
  - The forming of sheet metals by the simultaneous application of tangential stretch and radial compression forces. The operation is done gradually by tangential contact with the die member. This type of forming is characterized by very close dimensional control.
- **radial forging**
  - A process using two or more moving anvils or dies for producing shafts with constant or varying diameters along their length or tubes with internal or external variations. Often incorrectly referred to as rotary forging .
- **radial marks**
  - Lines on a fracture surface that radiate from the fracture origin and are visible to the unaided eye or at low magnification. Radial marks result from the intersection and connection of brittle fractures propagating at different levels. Also known as shear ledges. See also chevron pattern .
- **radiation damage**
  - A general term for the alteration of properties of a material arising from exposure to ionizing radiation (penetrating radiation), such as x-rays, gamma rays, neutrons, heavy-particle radiation, or fission fragments in nuclear fuel material. See also neutron embrittlement .
- **radioactive element**
  - An element that has at least one isotope that undergoes spontaneous nuclear disintegration to emit positive αparticles, negative βparticles, or γrays.
- **radioactivity**

  - (1) The property of the nuclei of some isotopes to spontaneously decay (lose energy). Usual mechanisms are emission of α, β, or other particles and splitting (fissioning). Gamma rays are frequently, but not always, given off in the process. (2) A particular component from a radioactive source, such as βradioactivity.
- **radiograph**
  - A photographic shadow image resulting from uneven absorption of penetrating radiation in a test object. See also radiography .
- **radiography**
  - A method of nondestructive inspection in which a test object is exposed to a beam of x-rays or γ rays and the resulting shadow image of the object is recorded on photographic film placed behind the object, or displayed on a viewing screen or television monitor (real-time radiography). Internal discontinuities are detected by observing and interpreting variations in the image caused by differences in thickness, density, or absorption within the test object. See also real-time radiography .
- **radius of bend**
  - The radius of the cylindrical surface of the pin or mandrel that comes in contact with the inside surface of the bend during bending. In the case of free or semiguided bends to 180° in which a shim or block is used, the radius of bend is one-half the thickness of the shim or block.
- **rake**
  - The angular relationship between the tooth face, or a tangent to the tooth face at a given point, and a given reference plane or line.
- **ram**
  - The moving or falling part of a drop hammer or press to which one of the dies is attached; sometimes applied to the upper flat die of a steam hammer. Also referred to as the slide .
- **ramming**
  - (1) Packing foundry sand, refractory, or other material into a compact mass. (2) The compacting of molding (foundry) sand in forming a mold.
- **random sequence**
  - A longitudinal welding sequence wherein the weld-bead increments are deposited at random to minimize distortion.
- **range of stress (S_r)**
  - The algebraic difference between the maximum and minimum stress in one cycle--that is, $S_r = S_{max} - S_{min}$.
- **rapid solidification**
  - The cooling or quenching of liquid (molten) metals at rates that range from 10^4 to 10^8 °C/s.
- **rare earth metal**
  - A group of 17 chemically similar metals that includes the elements scandium and yttrium (atomic numbers 21 and 39, respectively) and the lanthanide elements (atomic numbers 57 through 71).
- **ratcheting**
  - Progressive cyclic inelastic deformation (growth, for example) that occurs when a component or structure is subjected to a cyclic secondary stress superimposed on a sustained primary stress. The process is called thermal ratcheting when cyclic strain is induced by cyclic changes in temperature, and isothermal ratcheting when cyclic strain is mechanical in origin (even though accompanied by cyclic changes in temperature).
- **ratchet marks**
  - Lines or markings on a fatigue fracture surface that results from the intersection and connection of fatigue fractures propagating from multiple origins. Ratchet marks are parallel to the overall direction of crack propagation and are visible to the unaided eye or at low magnification.
- **rate of strain hardening**
  - Rate of change of true stress with respect to true strain in the plastic range.
- **rattail**
  - A surface imperfection on a casting, occurring as one or more irregular lines, caused by expansion of sand in the mold. Compare with buckle (2).
- **reaction sintering**
  - The sintering of a metal powder mixture consisting of at least two components that chemically react during the treatment.
- **reactive metal**

  - A metal that readily combines with oxygen at elevated temperatures to form very stable oxides, for example, titanium, zirconium, and beryllium. Reactive metals may also become embrittled by the interstitial absorption of oxygen, hydrogen, and nitrogen.
- **real-time radiography**
  - A method of nondestructive inspection in which a two-dimensional radiographic image can be immediately displayed on a viewing screen or television monitor. This technique does not involve the creation of a latent image; instead, the unabsorbed radiation is converted into an optical or electronic signal, which can be viewed immediately or can be processed in near real time with electronic and video equipment. See also radiography .
- **reaming**
  - An operation in which a previously formed hole is sized and contoured accurately by using a rotary cutting tool (reamer) with one or more cutting elements (teeth). The principal support for the reamer during the cutting action is obtained from the workpiece.
- **recalescence**
  - (1) The increase in temperature that occurs after undercooling, because the rate of liberation of heat during transformation of a material exceeds the rate of dissipation of heat. (2) A phenomenon, associated with the transformation of γiron to αiron on cooling (supercooling) of iron or steel, that is revealed by the brightening (reglowing) of the metal surface owing to the sudden increase in temperature caused by the fast liberation of the latent heat of transformation. Contrast with decalescence .
- **recarburize**
  - (1) To increase the carbon content of molten cast iron or steel by adding carbonaceous material, high-carbon pig iron, or a high-carbon alloy. (2) To carburize a metal part to return surface carbon lost in processing; also known as carbon restoration.
- **recess**
  - A groove or depression in a surface.
- **recovery**
  - (1) The time-dependent portion of the decrease in strain following unloading of a specimen at the same constant temperature as the initial test. Recovery is equal to the total decrease in strain minus the instantaneous recovery. (2) Reduction or removal of work-hardening effects in metals without motion of large-angle grain boundaries. (3) The proportion of the desired component obtained by processing an ore, usually expressed as a percentage.
- **recrystallization**
  - (1) The formation of a new, strain-free grain structure from that existing in cold-worked metal, usually accomplished by heating. (2) The change from one crystal structure to another, as occurs on heating or cooling through a critical temperature. (3) A process, usually physical, by which one crystal species is grown at the expense of another or at the expense of others of the same substance but smaller in size. See also crystallization .
- **recrystallization annealing**
  - Annealing cold-worked metal to produce a new grain structure without phase change.
- **recrystallization temperature**
  - The approximate minimum temperature at which complete recrystallization of a cold-worked metal occurs within a specified time.
- **recrystallized grain size**
  - (1) The grain size developed by heating cold-worked metal. The time and temperature are selected so that, although recrystallization is complete, essentially no grain growth occurs. (2) In aluminum and magnesium alloys, the grain size after recrystallization, without regard to grain growth or the recrystallized conditions. See also recrystallization .
- **recuperator**
  - Equipment for transferring heat from gaseous products of combustion to incoming air or fuel. The incoming material passes through pipes surrounded by a chamber through which the outgoing gases pass.
- **red mud**
  - A residue, containing a high percentage of iron oxide, obtained in purifying bauxite in the production of alumina in the Bayer process.
- **redox potential**
  - This potential of a reversible oxidation-reduction electrode measured with respect to a reference electrode, corrected to the hydrogen electrode, in a given electrode.

- **redrawing**
    - The second and successive deep-drawing operations in which cup-like shells are deepened and reduced in cross-sectional dimensions. See also deep drawing .
- **reducing agent**
    - (1) A compound that causes reduction, thereby itself becoming oxidized. (2) A chemical that, at high temperatures, lowers the state of oxidation of other batch chemicals.
- **reducing atmosphere**
    - (1) A furnace atmosphere that tends to remove oxygen from substances or materials placed in the furnace. (2) A chemically active protective atmosphere that at elevated temperature will reduce metal oxides to their metallic state. Reducing atmosphere is a relative term and such an atmosphere may be reducing to one oxide but not to another oxide.
- **reducing flame**
    - (1) A gas flame produced with excess fuel in the inner flame. (2) A gas flame resulting from combustion of a mixture containing too much fuel or too little air. See also neutral flame and oxidizing flame .
- **reduction**
    - (1) In cupping and deep drawing, a measure of the percentage decrease from blank diameter to cup diameter, or of diameter reduction in redrawing. (2) In forging, rolling, and drawing, either the ratio of the original to final cross-sectional area or the percentage decrease in cross-sectional area. (3) A reaction in which there is a decrease in valence resulting from a gain in electrons. Contrast with oxidation .
- **reduction cell**
    - A pot or tank in which either a water solution of a salt or a fused salt is reduced electrolytically to form free metals or other substances.
- **reduction in area (RA)**
    - The difference between the original cross-sectional area of a tensile specimen and the smallest area at or after fracture as specified for the material undergoing testing. Also known as reduction of area.
- **reel**
    - (1) A spool or hub for coiling or feeding wire or strip. (2) To straighten and planish a round bar by passing it between contoured rolls.
- **reel breaks**
    - Transverse breaks or ridges on successive inner laps of a coil that results from crimping of the lead end of the coil into a gripping segmented mandrel. Also called reel kinks.
- **reference electrodes**
    - A nonpolarizable electrode with a known and highly reproducible potential used for potentiometric and voltammetric analyses. See also calomel electrode .
- **reference material**
    - In materials characterization, a material of definite composition that closely resembles in chemical and physical nature the material with which an analyst expects to deal; used for calibration or standardization. See also standard reference material .
- **refining**
    - The branch of process metallurgy dealing with the purification of crude or impure metals. Compare with extractive metallurgy .
- **reflowing**
    - Melting of an electrodeposit followed by solidification. The surface has the appearance and physical characteristics of a hot dipped surface (especially tin or tin alloy plates). Also called flow brightening .
- **refractory**
    - (1) A material (usually an inorganic, nonmetallic, ceramic material) of very high melting point with properties that make it suitable for such uses as furnace linings and kiln construction. (2) The quality of resisting heat.
- **refractory alloy**
    - (1) A heat-resistant alloy. (2) An alloy having an extremely high melting point. See also refractory metal . (3) An alloy difficult to work at elevated temperatures.
- **refractory metal**
    - A metal having an extremely high melting point and low vapor pressure; for example, niobium, tantalum, molybdenum, tungsten, and rhenium.

- **regenerator**
    - Same as recuperator except that the gaseous products or combustion heat brick checkerwork in a chamber connected to the exhaust side of the furnace while the incoming air and fuel are being heated by the brick checkerwork in a second chamber, connected to the entrance side. At intervals, the gas flow is reversed so that incoming air and fuel contact hot checkerwork while that in the second chamber is being reheated by exhaust gases.
- **regulator**
    - A device for controlling the delivery of welding or cutting gas at some substantially constant pressure.
- **reliability**
    - A quantitative measure of the ability of a product or service to fulfill its intended function for a specified period of time.
- **relieving**
    - Buffing or other abrasive treatment of the high points of an embossed metal surface to produce highlights that contrast with the finish in the recesses.
- **remanence**
    - The magnetic induction remaining in a magnetic circuit after removal of the applied magnetizing force. Sometimes called remanent induction.
- **repressing**
    - The application of pressure to a previously pressed and sintered powder metallurgy compact, usually for the purpose of improving some physical or mechanical property or for dimensional accuracy.
- **residual elements**
    - Small quantities of elements unintentionally present in an alloy.
- **residual stress**
    - (1) The stress existing in a body at rest, in equilibrium, at uniform temperature, and not subjected to external forces. Often caused by the forming or thermal processing curing process. (2) An internal stress not depending on external forces resulting from such factors as cold working, phase changes, or temperature gradients. (3) Stress present in a body that is free of external forces or thermal gradients. (4) Stress remaining in a structure or member as a result of thermal or mechanical treatment or both. Stress arises in fusion welding primarily because the weld metal contracts on cooling from the solidus to room temperature.
- **resilience**
    - (1) The amount of energy per unit volume released on unloading. (2) The capacity of a material, by virtue of high yield strength and low elastic modulus, to exhibit considerable elastic recovery on release of load.
- **resinoid wheel**
    - A grinding wheel bonded with a synthetic resin.
- **resist**
    - (1) Coating material used to mask or protect selected areas of a substrate from the action of an etchant, solder, or plating. (2) A material applied to prevent flow of brazing filler metal into unwanted areas.
- **resistance brazing**
    - A brazing process in which the heat required is obtained from the resistance to electric current flow in a circuit of which the workpiece is a part.
- **resistance seam welding**
    - A resistance welding process that produces coalescence at the faying surfaces of overlapped parts progressively along a length of a joint. The weld may be made with overlapping weld nuggets, a continuous weld nugget, or by forging the joint as it is heated to the welding temperature by resistance to the flow of the welding current.
- **resistance soldering**
    - A soldering process in which the heat required is obtained from the resistance to electric current flow in a circuit of which the workpiece is a part.
- **resistance spot welding**
    - A resistance welding process that produces coalescence at the faying surfaces of a joint by the heat obtained from resistance to the flow of welding current through the workpieces from electrodes that serve to concentrate the welding current and pressure at the weld areas.
- **resistance welding**

    - A group of welding processes that produce coalescence of metals with resistance heating and pressure. See also flash welding , projection welding , resistance seam welding , and resistance spot welding .
- **resistance welding electrode**
    - The part(s) of a resistance welding machine through which the welding current and, in most cases, force are applied directly to the work. The electrode may be in the form of a rotating wheel, rotating bar, cylinder, plate, clamp, chuck, or modification thereof.
- **restraint**
    - Any external mechanical force that prevents a part from moving to accommodate changes in dimension due to thermal expansion or contraction. Often applied to weldments made while clamped in a fixture. Compare with constraint .
- **restriking**
    - (1) The striking of a trimmed but slightly misaligned or otherwise faulty forging with one or more blows to improve alignment, improve surface condition, maintain close tolerances, increase hardness, or effect other improvements. (2) A sizing operation in which coining or stretching is used to correct or alter profiles and to counteract distortion. (3) A salvage operation following a primary forging operation in which the parts involved are rehit in the same forging die in which the pieces were last forged.
- **retort**
    - A vessel used for distillation of volatile materials, as in separation of some metals and in destructive distillation of coal.
- **reverberatory furnace**
    - A furnace in which the flame used for melting the metal does not impinge on the metal surface itself, but is reflected off the walls of the root of the furnace. The metal is actually melted by the generation of heat from the walls and the roof of the furnace.
- **reverse-current cleaning**
    - Electrolytic cleaning in which a current is passed between electrodes through a solution, and the part is set up as the anode. Also called anodic cleaning .
- **reverse drawing**
    - Redrawing of a sheet metal part in a direction opposite to that of the original drawing.
- **reverse polarity**
    - See preferred term direct current electrode positive (DCEP) .
- **reverse redrawing**
    - A second drawing operation in a direction opposite to that of the original drawing.
- **rheocasting**
    - Casting of a continuously stirred semisolid metal slurry. The process involves vigorous agitation of the melt during the early stages of solidification to break up solid dendrites into small spherulites. See also semisolid metal forming .
- **rib**
    - A long V-shaped or radiused indentation used to strengthen large sheet metal panels. (2) A long, usually thin protuberance used to provide flexural strength to a forging (as in a rib-web forging).
- **rigging**
    - The engineering design, layout, and fabrication of pattern equipment for producing castings; including a study of the casting solidification program, feeding and gating, risering, skimmers, and fitting flasks.
- **rimmed steel**
    - A low-carbon steel containing sufficient iron oxide to give a continuous evolution of carbon monoxide while the ingot is solidifying, resulting in a case or rim of metal virtually free of voids. Sheet and strip products made from rimmed steel ingots have very good surface quality.
- **ring and circle shear**
    - A cutting or shearing machine with two rotary-disk cutters driven in unison and equipped with a circle attachment for cutting inside circles or rings from sheet metal, where it is impossible to start the cut at the edge of the sheet. One cutter shaft is inclined to the other to provide cutting clearance so that the outside section remains flat and usable. See also circle shear and rotary shear .
- **ring rolling**
    - The process of shaping weldless rings from pierced disks or shaping thick-wall ring-shaped blanks between rolls that control wall thickness, ring diameter, height, and contour.

- **riser**
  - A reservoir of molten metal connected to a casting to provide additional metal to the casting, required as the result of shrinkage before and during solidification.
- **riser blocks**
  - (1) Plates or pieces inserted between the top of a metalforming press bed or bolster and the die to decrease the height of the die space. (2) Spacers placed between bed and housings to increase shut height on a four-piece tie-rod straight-side press.
- **river pattern**
  - A term used in fractography to describe a characteristic pattern of cleavage steps running parallel to the local direction of crack propagation on the fracture surfaces of grains that have separated by cleavage.
- **riveting**
  - Joining of two or more members of a structure by means of metal rivets, the unheaded end being upset after the rivet is in place.
- **roasting**
  - Heating an ore to effect some chemical change that will facilitate smelting.
- **robber**
  - An extra cathode or cathode extension that reduces the current density on what would otherwise be a high-current-density area on work being electroplated.
- **Rochelle copper**
  - (1) A copper electrodeposit obtained from copper cyanide plating solution to which Rochelle salt (sodium potassium tartrate) has been added for grain refinement, better anode corrosion, and cathode efficiency. (2) The solution from which a Rochelle copper electrodeposit is obtained.
- **rock candy fracture**
  - A fracture that exhibits separated-grain facets; most often used to describe an intergranular fracture in a large-grained metal.
- **rocking shear**
  - A type of guillotine shear that utilizes a curved blade to shear sheet metal progressively from side to side by a rocker motion.
- **Rockwell hardness number**
  - A number derived from the net increase in the depth of impression as the load on an indenter is increased from a fixed minor load to a major load and then returned to the minor load. Various scales of Rockwell hardness numbers have been developed based on the hardness of the materials to be evaluated. The scales are designated by alphabetic suffixes to the hardness designation. For example, 64 HRC represents the Rockwell hardness number of 64 on the Rockwell C scale. See also Rockwell superficial hardness number .
- **Rockwell hardness test**
  - An indentation hardness test using a calibrated machine that utilizes the depth of indentation, under constant load, as a measure of hardness. Either a 120° diamond cone with a slightly rounded point or a 1.6 or 3.2 mm ($\frac{1}{16}$ or $\frac{1}{8}$ in.) diam steel ball is used as the indenter.
- **Rockwell superficial hardness number**
  - Like the Rockwell hardness number, the superficial Rockwell number is expressed by the symbol HR followed by a scale designation. For example, 81 HR30N represents the Rockwell superficial hardness number of 81 on the Rockwell 30N scale.
- **Rockwell superficial hardness test**
  - The same test as used to determine the Rockwell hardness number except that smaller minor and major loads are used. In Rockwell testing, the minor load is 10 kgf, and the major load is 60, 100, or 150 kgf. In superficial Rockwell testing, the minor load is 3 kgf, and major loads are 15, 30, or 45 kgf. In both tests, the indenter may be either a diamond cone or a steel ball, depending principally on the characteristics of the material being tested.
- **rod**
  - A solid round metal section 9.5 mm ($\frac{3}{8}$ in.) or greater in diameter, whose length is great in relation to its diameter.
- **rod mill**
  - (1) A hot mill for rolling rod. (2) A mill for fine grinding, somewhat similar to a ball mill, but employing long steel rods instead of balls to effect grinding.
- **roll bending**

    - Curving sheets, bars, and sections by means of rolls. See also bending rolls .
- **roll compacting**
    - Progressive compacting of metal powders by use of a rolling mill.
- **roller hearth furnace**
    - A modification of the pusher-type continuous furnace that provides for rollers in the hearth or muffle of the furnace whereby friction is greatly reduced and lightweight trays can be used repeatedly without risk of unacceptable distortion and damage to the work. See also pusher furnace .
- **roller leveler breaks**
    - Obvious transverse breaks usually about 3 to 6 mm ($\frac{1}{8}$ to $\frac{1}{4}$ in.) apart caused by the sheet metal fluting during roller leveling. These will not be removed by stretching.
- **roller leveler lines**
    - Same as leveler lines .
- **roller leveling**
    - Leveling by passing flat sheet metal stock through a machine having a series of small-diameter staggered rolls that are adjusted to produce repeated reverse bending.
- **roller stamping die**
    - An engraved roller used for impressing designs and markings on sheet metal.
- **roll flattening**
    - The flattening of metal sheets that have been rolled in packs by passing them separately through a two-high cold mill with virtually no deformation. Not to be confused with roller leveling .
- **roll forging**
    - A process of shaping stock between two driven rolls that rotate in opposite directions and have one or more matching sets of grooves in the rolls; used to produce finished parts or preforms for subsequent forging operations.
- **roll forming**
    - Metalforming through the use of power-driven rolls whose contour determines the shape of the product; sometimes used to denote power spinning.
- **rolling**
    - The reduction of the cross-sectional area of metal stock, or the general shaping of metal products, through the use of rotating rolls. See also rolling mills .
- **rolling-contact fatigue**
    - Repeated stressing of a solid surface due to rolling contact between it and another solid surface or surfaces. Continued rolling-contact fatigue of bearing or gear surfaces may result in rolling-contact damage in the form of subsurface fatigue cracks and/or material pitting and spallation.
- **rolling mills**
    - Machines used to decrease the cross-sectional area of metal stock and to produce certain desired shapes as the metal passes between rotating rolls mounted in a framework comprising a basic unit called a stand. Cylindrical rolls produce flat shapes; grooved rolls produce rounds, squares, and structural shapes. See also four-high mill , Sendzimir mill , and two-high mill .
- **roll straightening**
    - The straightening of metal stock of various shapes by passing it through a series of staggered rolls, the rolls usually being in horizontal and vertical planes, or by reeling in two-roll straightening machines.
- **roll threading**
    - See preferred term thread rolling .
- **roll welding**
    - Solid-state welding in which metals are heated, then welded together by applying pressure, with rolls, sufficient to cause deformation at the faying surfaces. See also forge welding .
- **root crack**
    - A crack in either the weld or heat-affected zone at the root of a weld.
- **rosette**
    - (1) Rounded configuration of microconstituents in metals arranged in whorls or radiating from a center. (2) Strain gages arranged to indicate at a single position strains in three different directions.
- **rotary forging**

  - A process in which the workpiece is pressed between a flat anvil and a swiveling (rocking) die with a conical working face; the platens move toward each other during forging. Also called orbital forging. Compare with radial forging .
- **rotary furnace**
  - A circular furnace constructed so that the hearth and workpieces rotate around the axis of the furnace during heating. Also called rotary hearth furnace.
- **rotary press**
  - A machine for forming powder metallurgy parts that is fitted with a rotating table carrying multiple die assemblies in which powder is compacted.
- **rotary retort furnace**
  - A continuous-type furnace in which the work advances by means of an internal spiral, which gives good control of the retention time within the heated chamber.
- **rotary shear**
  - A sheet metal cutting machine with two rotating-disk cutters mounted on parallel shafts driven in unison.
- **rotary swager**
  - A swaging machine consisting of a power-driven ring that revolves at high speed, causing rollers to engage cam surfaces and force the dies to deliver hammerlike blows on the work at high frequency. Both straight and tapered sections can be produced.
- **rotary swaging**
  - A bulk forming process for reducing the cross-sectional area or otherwise changing the shape of bars, tubes, or wires by repeated radial blows with one or more pairs of opposed dies.
- **rouge finish**
  - A highly reflective finish produced with rouge (finely divided, hydrated iron oxide) or other very fine abrasive, similar in appearance to the bright polish or mirror finish on sterling silver utensils.
- **rough blank**
  - A blank for a metalforming or drawing operation, usually of irregular outline, with necessary stock allowance for process metal, which is trimmed after forming or drawing to the desired size.
- **rough grinding**
  - Grinding without regard to finish, usually to be followed by a subsequent operation.
- **roughing stand**
  - The first stand (or several stands) of rolls through which a reheated billet passes in front of the finishing stands. See also rolling mills and stand .
- **rough machining**
  - Machining without regard to finish, usually to be followed by a subsequent operation.
- **roughness**
  - (1) Relatively finely spaced surface irregularities, the heights, widths, and directions of which establish the predominant surface pattern. (2) The microscopic peak-to-valley distances of surface protuberances and depressions. See also surface roughness .
- **rubber forming**
  - Forming a sheet metal wherein rubber or another resilient material is used as a functional die part. Processes in which rubber is employed only to contain the hydraulic fluid are not classified as rubber forming.
- **rubber-pad forming**
  - A sheet metal forming operation for shallow parts in which a confined, pliable rubber pad attached to the press slide (ram) is forced by hydraulic pressure to become a mating die for a punch or group of punches placed on the press bed or baseplate. Also known as the Guerin process . Variations of the Guerin process include the fluid-cell process , fluid forming , and Marforming process .
- **rubber wheel**
  - A grinding wheel made with a rubber bond.
- **runner**
  - (1) A channel through which molten metal flows from one receptacle to another. (2) The portion of the gate assembly of a casting that connects the sprue with the gate(s). (3) Parts of patterns and finished castings corresponding to the portion of the gate assembly described in (2).
- **runner box**
  - A distribution box that divides molten metal into several streams before it enters the casting mold cavity.

- **runout**
  - (1) The unintentional escape of molten metal from a mold, crucible, or furnace. (2) An imperfection in a casting caused by the escape of metal from the mold.
- **rupture stress**
  - The stress at failure. Also known as breaking stress or fracture stress .
- **rust**
  - A visible corrosion product consisting of hydrated oxides of iron. Applied only to ferrous alloys. See also white rust .
- **S**
- **sacrificial protection**
  - Reduction of corrosion of a metal in an electrolyte by galvanically coupling it to a more anodic metal; a form of cathodic protection.
- **saddling**
  - Forming a seamless metal ring by forging a pierced disk over a mandrel (or saddle).
- **sag**
  - An increase or decrease in the section thickness of a casting caused by insufficient strength of the mold sand of the cope or of the core.
- **salt bath heat treatment**
  - Heat treatment for metals carried out in a bath of molten salt.
- **salt fog test**
  - An accelerated corrosion test in which specimens are exposed to a fine mist of a solution usually containing sodium chloride, but sometimes modified with other chemicals. Also known as salt spray test.
- **salt spray test**
  - See salt fog test .
- **sample**
  - (1) One or more units of a product (or a relatively small quantity of a bulk material) withdrawn from a lot or process stream and then tested or inspected to provide information about the properties, dimensions, or other quality characteristics of the lot or process stream. (2) A portion of a material intended to be representative of the whole.
- **sand**
  - A granular material naturally or artificially produced by the disintegration or crushing of rocks or mineral deposits. In casting, the term denotes an aggregate, with an individual particle (grain) size of 0.06 to 2 mm (0.002 to 0.08 in.) in diameter, that is largely free of finer constituents, such as silt and clay, which are often present in natural sand deposits. The most commonly used foundry sand is silica; however, zircon, olivine, aluminum silicates, and other crushed ceramics are used for special applications.
- **sandblasting**
  - Abrasive blasting with sand. See also blasting or blast cleaning and compare with shotblasting .
- **sand casting**
  - Metal castings produced in sand molds.
- **sand hole**
  - A pit in the surface of a sand casting resulting from a deposit of loose sand on the surface of the mold.
- **sandwich rolling**
  - Rolling two or more strips of metal in a pack, sometimes to form a roll-welded composite.
- **satin finish**
  - A diffusely reflecting surface finish on metals, lustrous but not mirrorlike. One type is a butler finish.
- **saw gumming**
  - In saw manufacture, grinding away of punch marks or milling marks in the gullets (spaces between the teeth) and, in some cases, simultaneous sharpening of the teeth; in reconditioning of worn saws, restoration of the original gullet size and shape.
- **sawing**
  - Using a toothed blade or disk to sever parts or cut contours.
- **scab**
  - A defect on the surface of a casting that appears as a rough, slightly raised surface blemish, crusted over by a thin porous layer of metal, under which is a honeycomb or cavity that usually

contains a layer of sand; defect common to thin-wall portions of the casting or around hot areas of the mold.

- **scale**
  - Surface oxidation, consisting of partially adherent layers of corrosion products, left on metals by heating or casting in air or in other oxidizing atmospheres.
- **scale pit**
  - (1) A surface depression formed on a forging due to scale remaining in the dies during the forging operation. (2) A pit in the ground in which scale (such as that carried off by cooling water from rolling mills) is allowed to settle out as one step in the treatment of effluent waste water.
- **scaling**
  - (1) Forming a thick layer of oxidation products on metals at high temperature. Scaling should be distinguished from rusting, which involves the formation of hydrated oxides. See also rust . (2) Depositing water-insoluble constituents on a metal surface, as in cooling tubes and water boilers.
- **scalping**
  - Removing surface layers from an ingot, billet, or slab.
- **scanning Auger microscopy (SAM)**
  - An analytical technique that measures the lateral distribution of elements on the surface of a material by recording the intensity of their Auger electrons versus the position of the electron beam.
- **scarfing**
  - Cutting surface areas of metal objects, ordinarily by using an oxyfuel gas torch. The operation permits surface imperfections to be cut from ingots, billets, or the edges of plate that are to be beveled for butt welding. See also chipping .
- **Scleroscope hardness number (HSc or HSd)**
  - A number related to the height of rebound of a diamond-tipped hammer dropped on the material being tested. It is measured on a scale determined by dividing into 100 units the average rebound of the hammer from a quenched (to maximum hardness) and untempered AISI W-5 tool steel test block.
- **Scleroscope hardness test**
  - A dynamic indentation hardness test using a calibrated instrument that drops a diamond-tipped hammer from a fixed height onto the surface of the material being tested. The height of rebound of the hammer is a measure of the hardness of the material.
- **scorification**
  - Oxidation, in the presence of fluxes, of molten lead containing precious metals, to partly remove the lead in order to concentrate the precious metals.
- **scoring**
  - (1) The formation of severe scratches in the direction of sliding. (2) The act of producing a scratch or narrow groove in a surface by causing a sharp instrument to move along that surface. (3) The marring or scratching of any formed metal part by metal pickup on the punch or die. (4) The reduction in thickness of a material along a line to weaken it intentionally along that line.
- **scouring**
  - (1) A wet or dry cleaning process involving mechanical scrubbing. (2) A wet or dry mechanical finishing operation, using fine abrasive and low pressure, carried out by hand or with a cloth or wire wheel to produce satin or butler-type finishes.
- **scrap**
  - (1) Products that are discarded because they are defective or otherwise unsuitable for sale. (2) Discarded metallic material, from whatever source, that may be reclaimed through melting and refining.
- **scratch hardness**
  - The hardness of a metal determined by the width of a scratch made by drawing a cutting point across the surface under a given pressure.
- **screen**
  - (1) The woven wire or fabric cloth, having square openings, used in a sieve for retaining particles greater than the particular mesh size. U.S. standard, ISO, or Tyler screen sizes are commonly used. (2) One of a set of sieves, designated by the size of the openings, used to classify granular aggregates such as sand, ore, or coke by particle size. (3) A perforated sheet placed in the gating system of a mold to separate impurities from the molten metal.
- **screw dislocation**

    - See dislocation .
- **screw press**
    - A high-speed press in which the ram is activated by a large screw assembly powered by a drive mechanism.
- **scuffing**
    - (1) Localized damage caused by the occurrence of solid-phase welding between sliding surfaces, without local surface melting. (2) A mild degree of galling that results from the welding of asperities due to frictional heat. The welded asperities break, causing surface degradation.
- **seal coat**
    - Material applied to infiltrate the pores of a thermal spray deposit.
- **sealing**
    - (1) Closing pores in anodic coatings to render them less absorbent. (2) Plugging leaks in a casting by introducing thermosetting plastics into porous areas and subsequently setting the plastic with heat.
- **seal weld**
    - Any weld designed primarily to provide a specific degree of tightness against leakage.
- **seam**
    - (1) On a metal surface, an unwelded fold or lap that appears as a crack, usually resulting from a discontinuity. (2) A surface defect on a casting related to but of lesser degree than a cold shut . (3) A ridge on the surface of a casting caused by a crack in the mold face.
- **seam weld**
    - A continuous weld made between or upon overlapping members, in which coalescence may start and occur on the faying surfaces, or may have proceeded from the outer surface of one member. The continuous weld may consist of a single weld bead or a series of overlapping spot welds.
- **seam welding**
    - See arc seam weld and resistance seam welding .
- **season cracking**
    - An obsolete historical term usually applied to stress-corrosion cracking of brass.
- **secondary alloy**
    - Any alloy whose major constituent is obtained from recycled scrap metal.
- **secondary creep**
    - See creep.
- **secondary ion mass spectroscopy (SIMS)**
    - An analytical technique that measures the masses of ions emitted from the surface of a material when exposed to a beam of incident ions. The incident ions are usually monoenergetic and are all of the same species, for example, 5 keV Ne^+ ions.
- **secondary metal**
    - Metal recovered from scrap by remelting and refining.
- **sectioning**
    - The removal of a conveniently sized, representative specimen from a larger sample for metallographic inspection. Sectioning methods include shearing, sawing (using hacksaws, band saws, and diamond wire saws), abrasive cutting, and electrical discharge machining.
- **segment die**
    - A die made of parts that can be separated for ready removal of the workpiece. Synonymous with split die .
- **segregation**
    - (1) Nonuniform distribution of alloying elements, impurities, or microphases in metals and alloys. (2) A casting defect involving a concentration of alloying elements at specific regions, usually as a result of the primary crystallization of one phase with the subsequent concentration of other elements in the remaining liquid. Microsegregation refers to normal segregation on a microscopic scale in which material richer in an alloying element freezes in successive layers on the dendrites (coring) and in constituent network. Macrosegregation refers to gross differences in concentration (for example, from one area of a casting to another). See also inverse segregation and normal segregation .
- **segregation banding**
    - Inhomogeneous distribution of alloying elements aligned in filaments or plates parallel to the direction of working.
- **seizing**

  - The stopping of a moving part by a mating surface as a result of excessive friction.
- **seizure**
  - The stopping of relative motion as the result of interfacial friction. Seizure may be accompanied by gross surface welding. The term is sometimes used to denote scuffing .
- **Sejournet process**
  - See Ugine-Sejournet process .
- **selective heating**
  - Intentionally heating only certain portions of a workpiece.
- **selective leaching**
  - Corrosion in which one element is preferentially removed from an alloy, leaving a residue (often porous) of the elements that are more resistant to the particular environment. Also called dealloying or parting. See also decarburization , decobaltification , denickelification , dezincification , and graphitic corrosion .
- **selective quenching**
  - Quenching only certain portions of an object.
- **self-diffusion**
  - Thermally activated movement of an atom to a new site in a crystal of its own species, as, for example, a copper atom within a crystal of copper.
- **self-hardening steel**
  - See preferred term air-hardening steel .
- **self-lubricating material**
  - Any solid material that shows low friction without application of a lubricant.
- **semiautomatic arc welding**
  - Arc welding with equipment that controls only the filler metal feed. The advance of the welding is manually controlled.
- **semiautomatic plating**
  - Plating in which prepared cathodes are mechanically conveyed through the plating baths, with intervening manual transfers.
- **semiconductor**
  - A solid crystalline material whose electrical resistivity is intermediate between that of a metal conductor and an insulator, ranging from about 10^{-3} to 10^{8} $\Omega\cdot$ cm, and is usually strongly temperature dependent.
- **semifinisher**
  - An impression in a series of forging dies that only approximates the finish dimensions of the forging. Semifinishers are often used to extend die life or the finishing impression, to ensure proper control of grain flow during forging, and to assist in obtaining desired tolerances.
- **semifinishing**
  - Preliminary operations performed prior to finishing.
- **semiguided bend**
  - The bend obtained by applying a force directly to the specimen in the portion that is to be bent. The specimen is either held at one end and forced around a pin or rounded edge or is supported near the ends and bent by a force applied on the side of the specimen opposite the supports and midway between them. In some instances, the bend is started in this manner and finished in the manner of a free bend.
- **semikilled steel**
  - Steel that is incompletely deoxidized and contains sufficient dissolved oxygen to react with the carbon to form carbon monoxide and thus offset solidification shrinkage.
- **semipermanent mold**
  - A permanent mold in which sand cores or plaster are used.
- **semisolid metal forming**
  - A two-step casting/forging process in which a billet is cast in a mold equipped with a mixer that continuously stirs the thixotropic melt, thereby breaking up the dendritic structure of the casting into a fine-grained spherical structure. After cooling, the billet is stored for subsequent use. Later, a slug from the billet is cut, heated to the semisolid state, and forged in a die. Normally the cast billet is forged when 30 to 40% is in the liquid state. See also rheocasting .
- **sensitization**
  - In austenitic stainless steels, the precipitation of chromium carbides, usually at grain boundaries, on exposure to temperatures of about 540 to 845 °C (about 1000 to 1550 °F), leaving the grain

  - boundaries depleted of chromium and therefore susceptible to preferential attack by a corroding medium. Welding is the most common cause of sensitization. Weld decay (sensitization) caused by carbide precipitation in the weld heat-affected zone leads to intergranular corrosion.
- **sensitizing heat treatment**
  - A heat treatment, whether accidental, intentional, or incidental (as during welding), that causes precipitation of constituents at grain boundaries, often causing the alloy to become susceptible to intergranular corrosion or intergranular stress-corrosion cracking. See also sensitization .
- **Sendzimir mill**
  - A type of cluster mill with small-diameter work rolls and larger-diameter backup rolls, backed up by bearings on a shaft mounted eccentrically so that it can be rotated to increase the pressure between the bearing and the backup rolls. Used to roll precision and very thin sheet and strip.
- **series welding**
  - Resistance welding in which two or more spot, seam, or projection welds are made simultaneously by a single welding transformer with three or more electrodes forming a series circuit.
- **settling**
  - (1) Separation of solids from suspension in a fluid of lower density, solely by gravitational effects. (2) A process for removing iron from liquid magnesium alloys by holding the melt at a low temperature after manganese has been added to it.
- **severity of quench**
  - Ability of quenching medium to extract heat from a hot steel workpiece; expressed in terms of the Grossmann number (H).
- **shadowing**
  - Directional deposition of carbon or a metallic film on a plastic replica so as to highlight features to be analyzed by transmission electron microscopy. Most often used to provide maximum detail and resolution of the features of fracture surfaces.
- **shakeout**
  - Removal of castings from a sand mold. See also knockout .
- **shaker-hearth furnace**
  - A continuous type furnace that uses a reciprocating shaker motion to move the parts along the hearth.
- **shank**
  - (1) The portion of a die or tool by which it is held in position in a forging unit or press. (2) The handle for carrying a small ladle or crucible. (3) The main body of a lathe tool. If the tool is an inserted type, the shank is the portion that supports the insert.
- **shank-type cutter**
  - A cutter having a straight or tapered shank to fit into a machine-tool spindle or adapter.
- **shape memory alloys**
  - A group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure.
- **shaping**
  - Producing flat surfaces using single-point tools. The work is held in a vise or fixture or is clamped directly to the table. The ram supporting the tool is reciprocated in a linear motion past the work.
- **shatter crack**
  - See flake .
- **shaving**
  - (1) As a finishing operation, the accurate removal of a thin layer of a work surface by straightline motion between a cutter and the surface. (2) Trimming parts such as stampings, forgings, and tubes to remove uneven sheared edges or to improve accuracy.
- **shear**
  - (1) The type of force that causes or tends to cause two contiguous parts of the same body to slide relative to each other in a direction parallel to their plane of contact. (2) A machine or tool for cutting metal and other material by the closing motion of two sharp, closely adjoining edges; for example, squaring shear and circular shear. (3) An inclination between two cutting edges, such as between two straight knife blades or between the punch cutting edge and the die cutting edge, so that a reduced area will be cut each time. This lessens the necessary force, but increases the

required length of the working stroke. This method is referred to as angular shear. (4) The act of cutting by shearing dies or blades, as in shearing lines.

- **shear angle**
  - The angle that the shear plane, in metal cutting, makes with the work surface.
- **shear bands**
  - (1) Bands of very high shear strain that are observed during rolling of sheet metal. During rolling, these form at approximately 35° to the rolling plane, parallel to the transverse direction. They are independent of grain orientation and at high strain rates traverse the entire thickness of the rolled sheet. (2) Highly localized deformation zones in metals that are observed at very high strain rates, such as those produced by high velocity (100 to 3600 m/s, or 330 to 11,800 ft/s) projectile impacts or explosive rupture.
- **shear fracture**
  - A mode of fracture in crystalline materials resulting from translation along slip planes that are preferentially oriented in the direction of the shearing stress.
- **shear ledges**
  - See radial marks .
- **shear lip**
  - A narrow, slanting ridge along the edge of a fracture surface. The term sometimes also denotes a narrow, often crescent-shaped, fibrous region at the edge of a fracture that is otherwise of the cleavage type, even though this fibrous region is in the same plane as the rest of the fracture surface.
- **shear modulus (*G*)**
  - The ratio of shear stress to the corresponding shear strain for shear stresses below the proportional limit of the material. Values of shear modulus are usually determined by torsion testing. Also known as modulus of rigidity.
- **shear plane**
  - A confined zone along which shear takes place in metal cutting. It extends from the cutting edge to the work surface.
- **shear strain**
  - The tangent of the angular change, caused by a force between two lines originally perpendicular to each other through a point in a body. Also called angular strain.
- **shear stress**
  - (1) The stress component tangential to the plane on which the forces act. (2) A stress that exists when parallel planes in metal crystals slide across each other.
- **sheet**
  - A flat-rolled metal product of some maximum thickness and minimum width arbitrarily dependent on the type of metal. It has a width-to-thickness ratio greater than about 50. Generally, such flat products under 6.5 mm ($\frac{1}{4}$ in.) thick are called sheets, and those 6.5 mm ($\frac{1}{4}$ in.) thick and over are called plates.
- **sheet forming**
  - The plastic deformation of a piece of sheet metal by tensile loads into a three-dimensional shape, often without significant changes in sheet thickness or surface characteristics. Compare with bulk forming .
- **shelf roughness**
  - Roughness on upward-facing surfaces where undissolved solids have settled on parts during a plating operation.
- **shell**
  - (1) A hollow structure or vessel. (2) An article formed by deep drawing. (3) The metal sleeve remaining when a billet is extruded with a dummy block of somewhat smaller diameter. (4) In shell molding, a hard layer of sand and thermosetting plastic or resin formed over a pattern and used as the mold wall. (5) A tubular casting used in making seamless drawn tube. (6) A pierced forging.
- **shell core**
  - A shell-molded sand core.
- **shell hardening**
  - A surface-hardening process in which a suitable steel workpiece, when heated through and quench hardened, develops a martensite layer or shell that closely follows the contour of the

piece and surrounds a core of essentially pearlitic transformation product. This result is accomplished by a proper balance among section size, steel hardenability, and severity of quench.

- **shelling**
  - (1) A term used in railway engineering to describe an advanced phase of spalling. (2) A mechanism of deterioration of coated abrasive products in which entire abrasive grains are removed from the coating that holds the abrasive to the backing layer of the product.
- **shell molding**
  - A foundry process in which a mold is formed from thermosetting resin-bonded sand mixtures brought in contact with preheated (150 to 260 °C, or 300 to 500 °F) metal patterns, resulting in a firm shell with a cavity corresponding to the outline of the pattern. Also called Croning process .
- **shielded metal arc cutting**
  - A metal arc cutting process in which metals are severed by melting them with the heat of an arc between a covered metal electrode and the base metal.
- **shielded metal arc welding (SMAW)**
  - An arc welding process that produces coalescence of metals by heating them with an arc between a covered metal electrode and the workpieces. Shielding is obtained from decomposition of the electrode covering. Pressure is not used, and filler metal is obtained from the electrode. Also commonly referred to as stick welding.
- **shielding gas**
  - (1) Protective gas used to prevent atmospheric contamination during welding. (2) A stream of inert gas directed at the substrate during thermal spraying so as to envelop the plasma flame and substrate; intended to provide a barrier to the atmosphere in order to minimize oxidation.
- **shift**
  - A casting imperfection caused by mismatch of cope and drag or of cores and molds.
- **shim**
  - A thin piece of material used between two surfaces to obtain a proper fit, adjustment, or alignment.
- **shimmy die**
  - See flat edge trimmer .
- **shock load**
  - The sudden application of an external force that results in a very rapid buildup of stress--for example, piston loading in internal combustion engines.
- **shoe**
  - (1) A metal block used in a variety of bending operations to form or support the part being processed. (2) An anvil cap or sow block.
- **Shore hardness test**
  - Same as Scleroscope hardness test .
- **short-circuiting transfer**
  - In consumable electrode arc welding, a type of metal transfer similar to globular transfer, but in which the drops are so large that the arc is short circuited momentarily during the transfer of each drop to the weld pool. Compare with globular transfer and spray transfer .
- **shortness**
  - A form of brittleness in metal. It is designated as cold shortness or hot shortness to indicate the temperature range in which the brittleness occurs.
- **short transverse**
  - See transverse direction .
- **shot**
  - (1) Small, spherical particles of metal. (2) The injection of molten metal into a die casting die. The metal is injected so quickly that it can be compared to the shooting of a gun.
- **shotblasting**
  - Blasting with metal shot; usually used to remove deposits or mill scale more rapidly or more effectively than can be done by sandblasting.
- **shot peening**
  - A method of cold working metals in which compressive stresses are induced in the exposed surface layers of parts by the impingement of a stream of shot, directed at the metal surface at high velocity under controlled conditions.
- **shotting**

  - The production of shot by pouring molten metal in finely divided streams. Solidified spherical particles are formed during descent in a tank of water.
- **shrinkage**
  - (1) The contraction of metal during cooling after hot forging. Die impressions are made oversize according to precise shrinkage scales to allow the forgings to shrink to design dimensions and tolerances. (2) See casting shrinkage .
- **shrinkage cavity**
  - A void left in cast metal as a result of solidification shrinkage. Shrinkage cavities can appear as either isolated or interconnected irregularly shaped voids. See also casting shrinkage .
- **shrinkage cracks**
  - Cracks that form in metal as a result of the pulling apart of grains by contraction before complete solidification. See also hot tear .
- **shrinkage rule**
  - A measuring ruler with graduations expanded to compensate for the change in the dimensions of the solidified casting as it cools in the mold.
- **shroud**
  - A protective, refractory-lined metal-delivery system to prevent reoxidation of molten steel when it is poured from ladle to tundish to mold during continuous casting.
- **shut height**
  - For a metalforming press, the distance from the top of the bed to the bottom of the slide with the stroke down and adjustment up. In general, it is the maximum die height that can be accommodated for normal operation, taking the bolster plate into consideration. See also bolster .
- **side milling**
  - Milling with cutters having peripheral and side teeth. They are usually profile sharpened but may be form relieved.
- **sieve**
  - A standard wire mesh or screen used in graded sets to determine the mesh size or particle size distribution of particulate and granular solids. See also sieve analysis .
- **sieve analysis**
  - A method of determining particle size distribution, usually expressed as the weight percentage retained upon each of a series of standard screens of decreasing mesh size.
- **sieve classification**
  - The separation of powder into particle size ranges by the use of a series of graded sieves. Also called screen analysis.
- **sieve fraction**
  - That portion of a powder sample that passes through a sieve of specified number and is retained by some finer mesh sieve of specified number. See also sieve analysis .
- **sigma phase**
  - A hard, brittle, nonmagnetic intermediate phase with a tetragonal crystal structure, containing 30 atoms per unit cell, space group, *P*4/*mnm*, occurring in many binary and ternary alloys of the transition elements. The composition of this phase in the various systems is not the same, and the phase usually exhibits a wide range in homogeneity. Alloying with a third transition element usually enlarges the field homogeneity and extends it deep into the ternary section.
- **sigma-phase embrittlement**
  - Embrittlement of iron-chromium alloys (most notably austenitic stainless steels) caused by precipitation at grain boundaries of the hard, brittle intermetallic σphase during long periods of exposure to temperatures between approximately 560 and 980 °C (1050 and 1800 °F). Sigma-phase embrittlement results in severe loss in toughness and ductility and can make the embrittled material susceptible to intergranular corrosion. See also sensitization .
- **siliconizing**
  - Diffusing silicon into solid metal, usually low-carbon steels, at an elevated temperature in order to improve corrosion or wear resistance.
- **silky fracture**
  - A metal fracture in which the broken metal surface has a fine texture, usually dull in appearance. Characteristic of tough and strong metals. Contrast with crystalline fracture and granular fracture .
- **silver soldering**

    - Nonpreferred term used to denote brazing with a silver-base filler metal. See preferred terms furnace brazing , induction brazing , and torch brazing .
- **single-action press**
    - A metalforming press that provides pressure from one side.
- **single impulse welding**
    - A resistance welding process variation in which spot, projection, or upset welds are made with a single impulse.
- **single-point tool**
    - A cutting tool having one face and one continuous cutting edge.
- **single-stand mill**
    - A rolling mill designed such that the product contacts only two rolls at a given moment. Contrast with tandem mill .
- **single welded joint**
    - In arc and gas welding, any joint welded from one side only.
- **sinkhead**
    - Same as riser .
- **sinking**
    - (1) The operation of machining the impression of a desired forging into die blocks. (2) See tube sinking .
- **sintered density**
    - The quotient of the mass (weight) over the volume of the sintered body expressed in grams per cubic centimeter.
- **sintering**
    - The bonding of adjacent surfaces of particles in a mass of powder or a compact by heating. Sintering strengthens a powder mass and normally produces densification and, in powdered metals, recrystallization. See also liquid phase sintering and solid-state sintering .
- **size effect**
    - Effect of the dimensions of a piece of metal on its mechanical and other properties and on manufacturing variables such as forging reduction and heat treatment. In general, the mechanical properties are lower for a larger size.
- **sizing**
    - (1) Secondary forming or squeezing operations needed to square up, set down, flatten, or otherwise correct surfaces to produce specified dimensions and tolerances. See also restriking . (2) Some burnishing, broaching, drawing, and shaving operations are also called sizing. (3) A finishing operation for correcting ovality in tubing. (4) Final pressing of a sintered powder metallurgy part to obtain a desired dimension.
- **skelp**
    - The starting stock for making welded pipe or tubing; most often it is strip stock of suitable width, thickness, and edge configuration.
- **skim gate**
    - In foundry practice, a gating arrangement designed to prevent the passage of slag and other undesirable materials into a casting.
- **skimming**
    - Removing or holding back dirt or slag from the surface of the molten metal before or during pouring.
- **skin**
    - A thin outside metal layer, not formed by bonding as in cladding or electroplating, that differs in composition, structure, or other characteristics from the main mass of metal.
- **skin lamination**
    - In flat-rolled metals, a surface rupture resulting from the exposure of a subsurface lamination by rolling.
- **skin pass**
    - See temper rolling .
- **skiving**
    - (1) Removal of a material in thin layers or chips with a high degree of shear or slippage, or both, of the cutting tool. (2) A machining operation in which the cut is made with a form tool with its face so angled that the cutting edge progresses from one end of the work to the other as the tool feeds tangentially past the rotating workpiece.

- **skull**
  - (1) A layer of solidified metal or dross on the walls of a pouring vessel after the metal has been poured. (2) The unmelted residue from a liquated weld filler metal.
- **slab**
  - A flat-shaped semifinished rolled metal ingot with a width not less than 250 mm (10 in.) and a cross-sectional area not less than 105 cm^2 (16 $in.^2$).
- **slabbing mill**
  - A primary mill that produces slabs.
- **slab milling**
  - See preferred term peripheral milling .
- **slack quenching**
  - The incomplete hardening of steel due to quenching from the austenitizing temperature at a rate slower than the critical cooling rate for the particular steel, resulting in the formation of one or more transformation products in addition to martensite.
- **slag**
  - A nonmetallic product resulting from the mutual dissolution of flux and nonmetallic impurities in smelting, refining, and certain welding operations (see, for example, electroslag welding). In steelmaking operations, the slag serves to protect the molten metal from the air and to extract certain impurities.
- **slag inclusion**
  - (1) Slag or dross entrapped in a metal. (2) Nonmetallic solid material entrapped in weld metal or between weld metal and base metal.
- **slant fracture**
  - A type of fracture in metals, typical of plane-stress fractures, in which the plane of separation is inclined at an angle (usually about 45°) to the axis of applied stress.
- **slide**
  - The main reciprocating member of a metalforming press, guided in the press frame, to which the punch or upper die is fastened; sometimes called the ram . The inner slide of a double-action press is called the plunger or punch-holder slide; the outer slide is called the blankholder slide. The third slide of a triple-action press is called the lower slide, and the slide of a hydraulic press is often called the platen.
- **slime**
  - (1) A material of extremely fine particle size encountered in ore treatment. (2) A mixture of metals and some insoluble compounds that forms on the anode in electrolysis.
- **slip**
  - Plastic deformation by the irreversible shear displacement (translation) of one part of a crystal relative to another in a definite crystallographic direction and usually on specific crystallographic plane. Sometimes called glide.
- **slip band**
  - A group of parallel slip lines so closely spaced as to appear as a single line when observed under an optical microscope. See also slip line .
- **slip direction**
  - The crystallographic direction in which the translation of slip takes place.
- **slip flask**
  - A tapered flask that depends on a movable strip of metal to hold foundry sand in position. After closing the mold, the strip is refracted and the flask can be removed and reused. Molds thus made are usually supported by a mold jacket during pouring.
- **slip line**
  - Visible traces of slip planes on metal surfaces; the traces are (usually) observable only if the surface has been polished before deformation. The usual observation on metal crystals (under a light microscope) is of a cluster of slip lines known as a slip band .
- **slip plane**
  - The crystallographic plane in which slip occurs in a crystal.
- **slitting**
  - Cutting or shearing along single lines to cut strips from a metal sheet or to cut along lines of a given length or contour in a sheet or workpiece.
- **sliver**

  - An imperfection consisting of a very thin elongated piece of metal attached by only one end to the parent metal into whose surface it has been worked.
- **slot furnace**
  - A common batch furnace for heat treating metals where stock is charged and removed through a slot or opening.
- **slotting**
  - Cutting a narrow aperture or groove with a reciprocating tool in a vertical shaper or with a cutter, broach, or grinding wheel.
- **slow strain rate technique**
  - An experimental technique for evaluating susceptibility to stress-corrosion cracking. It involves pulling the specimen to failure in uniaxial tension at a controlled slow strain rate while the specimen is in the test environment and examining the specimen for evidence of stress-corrosion cracking.
- **slug**
  - (1) A short piece of metal to be placed in a die for forging or extrusion. (2) A small piece of material produced by piercing a hole in sheet material. See also blank .
- **slugging**
  - The act of adding a separate piece or pieces of material in a joint before or during welding that results in a welded joint not complying with design, drawing, or specification requirements.
- **slush casting**
  - A hollow casting usually made of an alloy with a low but wide melting temperature range. After the desired thickness of metal has solidified in the mold, the remaining liquid is poured out. Considered an obsolete practice.
- **smelting**
  - Thermal processing wherein chemical reactions take place to produce liquid metal from a beneficiated ore.
- **smith forging**
  - See hand forge (smith forge) .
- **smut**
  - A reaction product sometimes left on the surface of a metal after pickling, electroplating, or etching.
- **snagging**
  - (1) Heavy stock removal of superfluous material from a workpiece by using a portable or swing grinder mounted with a coarse grain abrasive wheel. (2) Offhand grinding on castings and forgings to remove surplus metal such as gate and riser pads, fins, and parting lines.
- **snake**
  - (1) The product formed by twisting and bending of hot metal rod prior to its next rolling process. (2) Any crooked surface imperfection in a plate, resembling a snake. (3) A flexible mandrel used in the inside of a shape to prevent flattening or collapse during a bending operation.
- **snap flask**
  - A foundry flask hinged on one corner so that it can be opened and removed from the mold for reuse before the metal is poured.
- **snap temper**
  - A precautionary interim stress-relieving treatment applied to high-hardenability steels immediately after quenching to prevent cracking because of delay in tempering them at the prescribed higher temperature.
- ***S*-*N* curve**
  - A plot of stress (S) against the number of cycles to failure (N). The stress can be the maximum stress (S_{max}) or the alternating stress amplitude (S_a). The stress values are usually nominal stress; i.e., there is no adjustment for stress concentration. The diagram indicates the S-N relationship for a specified value of the mean stress (S_m) or the stress ratio (A or R) and a specified probability of survival. For N a log scale is almost always used. For S a linear scale is used most often, but a log scale is sometimes used. Also known as S-N diagram.
- **soak cleaning**
  - Immersion cleaning without electrolysis.
- **soaking**
  - In heat treating of metals, prolonged holding at a selected temperature to effect homogenization of structure or composition. See also homogenizing .

- **soft magnetic material**
  - A ferromagnetic alloy that becomes magnetized readily upon application of a field and that returns to practically a nonmagnetic condition when the field is removed; an alloy with the properties of high magnetic permeability, low coercive force, and low magnetic hysteresis loss.
- **soft soldering**
  - See preferred term soldering .
- **soft temper**
  - Same as dead soft temper.
- **solder**
  - A filler metal used in soldering that has a liquidus not exceeding 450 °C (840 °F).
- **solderability**
  - The relative ease and speed with which a surface is wetted by molten solder.
- **solder embrittlement**
  - Reduction in mechanical properties of a metal as a result of local penetration of solder along grain boundaries.
- **soldering**
  - A group of processes that join metals by heating them to a suitable temperature below the solidus of the base metals and applying a filler metal having a liquidus not exceeding 450 °C (840 °F). Molten filler metal is distributed between the closely fitted surfaces of the joint by capillary action. See also solder .
- **soldering flux**
  - See flux .
- **soldering iron**
  - A soldering tool having an internally or externally heated metal bit usually made of copper.
- **solid cutters**
  - Cutters made of a single piece of material rather than a composite of two or more materials.
- **solidification**
  - The change in state from liquid to solid upon cooling through the melting temperature or melting range.
- **solidification range**
  - The temperature between the liquidus and the solidus.
- **solidification shrinkage**
  - The reduction in volume of metal from beginning to end of solidification. See also casting shrinkage .
- **solidification shrinkage crack**
  - A crack that forms, usually at elevated temperature, because of the internal (shrinkage) stresses that develop during solidification of a metal casting. Also termed hot crack.
- **solid lubricant**
  - Any solid used as a powder or thin film on a surface to provide protection from damage during relative movement and to reduce friction and wear.
- **solid metal embrittlement**
  - The occurrence of embrittlement in a material below the melting point of the embrittling species. See also liquid metal embrittlement .
- **solid solution**
  - A single, solid, homogeneous crystalline phase containing two or more chemical species.
- **solid-state sintering**
  - A sintering procedure for compacts or loose powder aggregates during which no component melts. Contrast with liquid phase sintering.
- **solid-state welding**
  - A group of welding processes that join metals at temperatures essentially below the melting points of the base materials, without the addition of a brazing filler metal. Pressure may or may not be applied to the joint. Examples include cold welding , diffusion welding , forge welding , hot pressure welding , and roll welding .
- **solidus**
  - (1) The highest temperature at which a metal or alloy is completely solid. (2) In a phase diagram, the locus of points representing the temperatures at which various compositions stop freezing upon cooling or begin to melt upon heating. See also liquidus .

- **solute**
  - The component of either a liquid or solid solution that is present to a lesser or minor extent; the component that is dissolved in the solvent.
- **solution heat treatment**
  - Heating an alloy to a suitable temperature, holding at that temperature long enough to cause one or more constituents to enter into solid solution, and then cooling rapidly enough to hold these constituents in solution.
- **solution potential**
  - Electrode potential where half-cell reaction involves only the metal electrode and its ion.
- **solvent**
  - The component of either a liquid or solid solution that is present to a greater or major extent; the component that dissolves the solute.
- **solvus**
  - In a phase or equilibrium diagram, the locus of points representing the temperature at which solid phases with various compositions coexist with other solid phases, that is, the limits of solid solubility.
- **sorbite (obsolete)**
  - A fine mixture of ferrite and cementite produced either by regulating the rate of cooling of steel or by tempering steel after hardening. The first type is very fine pearlite that is difficult to resolve under the microscope; the second type is tempered martensite.
- **sour gas**
  - A gaseous environment containing hydrogen sulfide and carbon dioxide in hydrocarbon reservoirs. Prolonged exposure to sour gas can lead to hydrogen damage, sulfide-stress cracking, and/or stress-corrosion cracking in ferrous alloys.
- **sow block**
  - A block of heat-treated steel placed between the anvil of the hammer and the forging die to prevent undue wear to the anvil. Sow blocks are occasionally used to hold insert dies. Also called anvil cap.
- **space lattice**
  - A regular, periodic array of points (lattice points) in space that represents the locations of atoms of the same kind in a perfect crystal. The concept may be extended, where appropriate, to crystalline compounds and other substances, in which case the lattice points often represent locations of groups of atoms of identical composition, arrangement, and orientation.
- **spade drill**
  - See preferred term flat drill .
- **spalling**
  - (1) Separation of particles from a surface in the form of flakes. The term spalling is commonly associated with rolling-element bearings and with gear teeth. Spalling is usually a result of subsurface fatigue and is more extensive than pitting. (2) The spontaneous chipping, fragmentation, or separation of a surface or surface coating. (3) A chipping or flaking of a surface due to any kind of improper heat treatment or material dissociation.
- **spangle**
  - The characteristic crystalline form in which a hot dipped zinc coating solidifies on steel strip.
- **spark testing**
  - A method used for the classification of ferrous alloys according to their chemical compositions, by visual examination of the spark pattern or stream that is thrown off when the alloys are held against a grinding wheel rotating at high speed.
- **spatter**
  - The metal particles expelled during arc or gas welding. They do not form part of the weld.
- **spatter loss**
  - The metal lost due to spatter.
- **specific energy**
  - In cutting or grinding, the energy expended or work done in removing a unit volume of material.
- **specimen**
  - A test object, often of standard dimensions and/or configuration, that is used for destructive or nondestructive testing. One or more specimens may be cut from each unit of a sample.
- **speed of travel**

    - In welding, the speed with which a weld is made along its longitudinal axis, usually measured in meters per second or inches per minute.
- **speiss**
    - Metallic arsenides and antimonides that result from smelting metal ores such as those of cobalt or lead.
- **spheroidal graphite**
    - Graphite of spheroidal shape with a polycrystalline radial structure. This structure can be obtained, for example, by adding cerium or magnesium to the melt. See also ductile iron and nodular graphite .
- **spheroidite**
    - An aggregate of iron or alloy carbides of essentially spherical shape dispersed throughout a matrix of ferrite.
- **spheroidized structure**
    - A microstructure consisting of a matrix containing spheroidal particles of another constituent.
- **spheroidizing**
    - Heating and cooling to produce a spheroidal or globular form of carbide in steel. Spheroidizing methods frequently used are: (1) Prolonged holding at a temperature just below Ae_1. (2) Heating and cooling alternatively between temperatures that are just above and just below Ae_1. (3) Heating to a temperature above Ae_1 or Ae_3 and then cooling very slowly in the furnace or holding at a temperature just below Ae_1. (4) Cooling at a suitable rate from the minimum temperature at which all carbide is dissolved to prevent the reformation of a carbide network, and then reheating in accordance with method 1 or 2 above. (Applicable to hypereutectoid steel containing a carbide network.)
- **spiegeleisen (spiegel)**
    - A pig iron containing 15 to 30% Mn and 4.5 to 6.5% C.
- **spindle**
    - (1) Shaft of a machine tool on which a cutter or grinding wheel may be mounted. (2) Metal shaft to which a mounted wheel is cemented.
- **spinning**
    - The forming of a seamless hollow metal part by forcing a rotating blank to conform to a shaped mandrel that rotates concentrically with the blank. In the typical application, a flat-rolled metal blank is forced against the mandrel by a blunt, rounded tool; however, other stock (notably, welded or seamless tubing) can be formed. A roller is sometimes used as the working end of the tool.
- **spinodal structure**
    - A fine, homogeneous mixture of two phases that form by the growth of composition waves in a solid solution during suitable heat treatment. The phases of a spinodal structure differ in composition from each other and from the parent phase, but have the same crystal structure as the parent phase.
- **spline**
    - Any of a series of longitudinal, straight projections on a shaft that fit into slots on a mating part to transfer rotation to or from the shaft.
- **split die**
    - A die made of parts that can be separated for ready removal of the workpiece. Also known as segment die.
- **split punch**
    - A segmented punch or a set of punches in a powder metallurgy forming press that allow(s) a separate positioning for different powder fill heights and compact levels in dual-step and multistep parts. See also stepped compact .
- **sponge**
    - A form of metal characterized by a porous condition that is the result of the decomposition or reduction of a compound without fusion. The term is applied to forms of iron, titanium, zirconium, uranium, plutonium, and the platinum-group metals.
- **sponge iron**
    - A coherent, porous mass of substantially pure iron produced by solid-state reduction of iron oxide (mill scale or iron ore).
- **spot drilling**

    - Making an initial indentation in a work surface, with a drill, to serve as a centering guide in a subsequent machining process.
- **spotfacing**
    - Using a rotary, hole-piloted end-facing tool to produce a flat surface normal to the axis of rotation of the tool on or slightly below the workpiece surface.
- **spot weld**
    - A weld made between or upon overlapping members in which coalescence may start and occur on the faying surfaces or may proceed from the surface of one member. The weld cross section is approximately circular.
- **spot welding**
    - See arc spot weld and resistance spot welding .
- **spray quenching**
    - A quenching process using spray nozzles to spray water or other liquids on a part. The quench rate is controlled by the velocity and volume of liquid per unit area per unit of time of impingement.
- **spray transfer**
    - In consumable-electrode arc welding, a type of metal transfer in which the molten filler metal is propelled across the arc as fine droplets. Compare with globular transfer and short-circuiting transfer .
- **springback**
    - (1) The elastic recovery of metal after stressing. (2) The extent to which metal tends to return to its original shape or contour after undergoing a forming operation. This is compensated for by overbending or by a secondary operation of restriking. (3) In flash, upset, or pressure welding, the deflection in the welding machine caused by the upset pressure.
- **spring temper**
    - A temper of nonferrous alloys and some ferrous alloys characterized by tensile strength and hardness about two-thirds of the way from full hard to extra spring temper.
- **sprue**
    - (1) The mold channel that connects the pouring basin with the runner or, in the absence of a pouring basin, directly into which molten metal is poured. Sometimes referred to as downsprue or downgate. (2) Sometimes used to mean all gates, risers, runners, and similar scrap that are removed from castings after shakeout.
- **sputtering**
    - The bombardment of a solid surface with a flux of energetic particles (ions) that results in the ejection of atomic species. The ejected material may be used as a source for deposition. See also physical vapor deposition .
- **square drilling**
    - Making square holes by means of a specially constructed drill made to rotate and also to oscillate so as to follow accurately the periphery of a square guide bushing or template.
- **squaring shear**
    - A machining tool, used for cutting sheet metal or plate, consisting essentially of a fixed cutting knife (usually mounted on the rear of the bed) and another cutting knife mounted on the front of a reciprocally moving crosshead, which is guided vertically in side housings. Corner angles are usually 90°.
- **squeeze casting**
    - A hybrid liquid metal forging process in which liquid metal is forced into a permanent mold by a hydraulic press.
- **stabilizing treatment**
    - (1) Before finishing to final dimensions, repeatedly heating a ferrous or nonferrous part to or slightly above its normal operating temperature and then cooling to room temperature to ensure dimensional stability in service. (2) Transforming retained austenite in quenched hardenable steels, usually by cold treatment. (3) Heating a solution-treated stabilized grade of austenitic stainless steel to 870 to 900 °C (1600 to 1650 °F) to precipitate all carbon as TiC, NbC, or TaC so that sensitization is avoided on subsequent exposure to elevated temperature.
- **stack cutting**
    - Thermal cutting of stacked metal plates arranged so that all the plates are severed by a single cut.
- **stack molding**

  - A foundry practice that makes use of both faces of a mold section, one face acting as the drag and the other as the cope. Sections, when assembled to other similar sections, form several tiers of mold cavities, all castings being poured together through a common sprue.
- **staggered-tooth cutters**
  - Milling cutters with alternate flutes of oppositely directed helixes.
- **stainless steel**
  - Any of several steels containing at least 10.5% Cr as the principal alloying element; they usually exhibit passivity in aqueous environments.
- **staking**
  - Fastening two parts together permanently by recessing one part within the other and then causing plastic flow at the joint.
- **stamping**
  - The general term used to denote all sheet metal pressworking. It includes blanking, shearing, hot or cold forming, drawing, bending, or coining.
- **stand**
  - A piece of rolling mill equipment containing one set of work rolls. In the usual sense, any pass of a cold- or hot-rolling mill. See also rolling mills .
- **standard electrode potential**
  - The reversible potential for an electrode process when all products and reactions are at unit activity on a scale in which the potential for the standard hydrogen half-cell is zero.
- **standard gold**
  - A gold alloy containing 10% Cu; at one time used for legal coinage in the United States.
- **standard reference material**
  - A reference material, the composition or properties of which are certified by a recognized standardizing agency or group.
- **starting sheet**
  - A thin sheet of metal used as the cathode in electrolyte refining.
- **state of strain**
  - A complete description of the deformation within a homogeneously deformed volume or at a point. The description requires, in general, the knowledge of the independent components of strain.
- **state of stress**
  - A complete description of the stresses within a homogeneously stressed volume or at a point. The description requires, in general, the knowledge of the independent components of stress.
- **static fatigue**
  - A term sometimes used to identify a form of hydrogen embrittlement in which a metal appears to fracture spontaneously under a steady stress less than the yield stress. There almost always is a delay between the application of stress (or exposure of the stressed metal to hydrogen) and the onset of cracking. More properly referred to as hydrogen-induced delayed cracking .
- **steadite**
  - A hard structural constituent of cast iron that consists of a binary eutectic of ferrite, containing some phosphorus in solution, and iron phosphide (Fe_3P). The eutectic consists of 10.2% P and 89.8% Fe. The melting temperature is 1050 °C (1920 °F).
- **Stead's brittleness**
  - A condition of brittleness that causes transcrystalline fracture in the coarse grain structure that results from prolonged annealing of thin sheets of low-carbon steel previously rolled at a temperature below about 705 °C (1300 °F). The fracture usually occurs at about 45° to the direction of rolling.
- **steam hammer**
  - A type of drop hammer in which the ram is raised for each stroke by a double-action steam cylinder and the energy delivered to the workpiece is supplied by the velocity and weight of the ram and attached upper die driven downward by steam pressure. The energy delivered during each stroke can be varied.
- **steam treatment**
  - The treatment of a sintered ferrous part in steam at temperatures between 510 and 595 °C (950 to 1100 °F) in order to produce a layer of black iron oxide (magnetite, or ferrous-ferric oxide, $FeO \cdot Fe_2O_3$) on the exposed surface for the purpose of increasing hardness and wear resistance.
- **Steckel mill**

    - A cold reducing mill having two working rolls and two backup rolls, none of which is driven. The strip is drawn through the mill by a power reel in one direction as far as the strip will allow and then reversed by a second power reel, and so on until the desired thickness is attained.
- **steel**
    - An iron-base alloy, malleable in some temperature ranges as initially cast, containing manganese, usually carbon, and often other alloying elements. In carbon steel and low-alloy steel, the maximum carbon is about 2.0%; in high-alloy steel, about 2.5%. The dividing line between low-alloy and high-alloy steels is generally regarded as being at about 5% metallic alloying elements.

      Steel is said to be differentiated from two general classes of "irons": the cast irons, on the high-carbon side and the relatively pure irons such as ingot iron, carbonyl iron, and electrolytic iron, on the low-carbon side. In some steels containing extremely low carbon, the manganese content is the principal differentiating factor, steel usually containing at least 0.25% and ingot iron considerably less.

- **step aging**
    - Aging of metals at two or more temperatures, by steps, without cooling to room temperature after each step. See also aging , and compare with interrupted aging and progressive aging .
- **stepped compact**
    - A powder metallurgy compact with one (dual step) or more (multistep) abrupt cross-sectional changes, usually obtained by pressing with split punches, each section of which uses a different pressure and a different rate of compaction. See also split punch .
- **stepped extrusion**
    - See extrusion .
- **step fracture**
    - Cleavage fractures that initiate on many parallel cleavage planes.
- **stereoscopic micrographs**
    - A pair of micrographs (or fractographs) of the same area, but taken from different angles so that the two micrographs when properly mounted and viewed reveal the structures of the objects in their three-dimensional relationships.
- **sterling silver**
    - A silver alloy containing at least 92.5% Ag, the remainder being unspecified but usually copper. Sterling silver is used for flat and hollow tableware and for various items of jewelry.
- **stick electrode**
    - A shop term for covered electrode .
- **stick welding**
    - See preferred term shielded metal arc welding .
- **sticker breaks**
    - Arc-shaped coil breaks, usually located near the center of sheet or strip.
- **stiffness**
    - (1) The rate of stress with respect to strain; the greater the stress required to produce a given strain, the stiffer the material is said to be. (2) The ability of a material or shape to resist elastic deflection. For identical shapes, the stiffness is proportional to the modulus of elasticity. For a given material, the stiffness increases with increasing moment of inertia, which is computed from cross-sectional dimensions.
- **stock**
    - A general term used to refer to a supply of metal in any form or shape and also to an individual piece of metal that is formed, forged, or machined to make parts.
- **stopoff**
    - A material used on the surfaces adjacent to the joint to limit the spread of soldering or brazing filler metal. See also resist .
- **stopper rod**
    - A device in a bottom-pour ladle for controlling the flow of metal through the nozzle into a mold. The stopper rod consists of a steel rod, protective refractory sleeves, and a graphite stopper head.
- **stopping off**
    - (1) Applying a resist. (2) Depositing a metal (copper, for example) in localized areas to prevent carburization, decarburization, or nitriding in those areas. (3) Filling in a portion of a mold cavity to keep out molten metal.

- **stradle milling**
  - Face milling a workpiece on both sides at once using two cutters spaced as required.
- **straightening**
  - (1) Any bending, twisting, or stretching operation to correct any deviation from straightness in bars, tubes, or similar long parts or shapes. This deviation can be expressed as either camber (deviation from a straight line) or as total indicator reading (TIR) per unit of length. (2) A finishing operation for correcting misalignment in a forging or between various sections of a forging. See also roll straightening .
- **straight polarity**
  - See preferred term direct current electrode negative (DCEN) .
- **strain**
  - The unit of change in the size or shape of a body due to force. Also known as nominal strain. The term is also used in a broader sense to denote a dimensionless number that characterizes the change in dimensions of an object during a deformation or flow process. See also engineering strain and true strain .
- **strain-age embrittlement**
  - A loss in ductility accompanied by an increase in hardness and strength that occurs when low-carbon steel (especially rimmed or capped steel) is aged following plastic deformation. The degree of embrittlement is a function of aging time and temperature, occurring in a matter of minutes at about 200 °C (400 °F), but requiring a few hours to a year at room temperature.
- **strain aging**
  - (1) Aging following plastic deformation. (2) The changes in ductility, hardness, yield point, and tensile strength that occur when a metal or alloy that has been cold worked is stored for some time. In steel, strain aging is characterized by a loss of ductility and a corresponding increase in hardness, yield point, and tensile strength.
- **strain energy**
  - The potential energy stored in a body by virtue of elastic deformation, equal to the work that must be done to produce this deformation.
- **strain hardening**
  - An increase in hardness and strength of metals caused by plastic deformation at temperatures below the recrystallization range. Also known as work hardening.
- **strain-hardening coefficient**
  - See strain-hardening exponent .
- **strain-hardening exponent**
  - The value of *n* in the relationship:

    $$\sigma = K \varepsilon^{n}$$

  - where σ is the true stress, ε is the true strain, and *K*, which is called the strength coefficient, is equal to the true stress at a true strain of 1.0. The strain-hardening exponent, also called "*n*-value," is equal to the slope of the true stress/true strain curve up to maximum load, when plotted on log-log coordinates. The *n*-value relates to the ability of as sheet metal to be stretched in metalworking operations. The higher the *n*-value, the better the formability (stretchability).
- **strain rate**
  - The time rate of straining for the usual tensile test. Strain as measured directly on the specimen gage length is used for determining strain rate. Because strain is dimensionless, the units of strain rate are reciprocal time.
- **strain-rate sensitivity (*m*-value)**
  - The increase in stress (σ) needed to cause a certain increase in plastic strain rate ($\dot{\varepsilon}$) at a given level of plastic strain (ε) and a given temperature (*T*):

    $$\text{Strain-rate sensitivity} = m = \left(\frac{\Delta \log \sigma}{\Delta \log \dot{\varepsilon}} \right)_{\varepsilon\, T}$$

- **strain rods**

    - (1) Rods sometimes used on gapframe metalforming presses to lessen the frame deflection. (2) Rods used to measure elastic strain and thus stresses, in frames of metalforming presses.
- **strain state**
    - See state of strain .
- **strand casting**
    - A generic term describing continuous casting of one or more elongated shapes such as billets, blooms, or slabs; if two or more shapes are cast simultaneously, they are often of identical cross section.
- **stranded electrode**
    - A composite filler metal electrode consisting of stranded wires that may mechanically enclose materials to improve properties, stabilize the arc, or provide shielding.
- **stray current**
    - (1) Current flowing through paths other than the intended circuit. (2) Current flowing in electrodeposition by way o an unplanned and undesired bipolar electrode that may be the tank itself or a poorly connected electrode.
- **stray-current corrosion**
    - Corrosion resulting from direct current flow through paths other than the intended circuit. For example, by an extraneous current in the earth.
- **stress**
    - The intensity of the internally distributed forces or components of forces that resist a change in the volume or shape of a material that is or has been subjected to external forces. Stress is expressed in force per unit area. Stress can be normal (tension or compression) or shear. See also compressive stress , engineering stress , mean stress , nominal stress , normal stress , residual stress , shear stress , tensile stress , and true stress .
- **stress amplitude**
    - One-half the algebraic difference between the maximum and minimum stresses in one cycle of a repetitively varying stress.
- **stress concentration**
    - On a macromechanical level, the magnification of the level of an applied stress in the region of a notch, void, hole, or inclusion.
- **stress concentration factor (K_t)**
    - A multiplying factor for applied stress that allows for the presence of a structural discontinuity such as a notch or hole; K_t equals the ratio of the greatest stress in the region of the discontinuity to the nominal stress for the entire section. Also called theoretical stress concentration factor.
- **stress corrosion**
    - Preferential attack of areas under stress in a corrosive environment, where such an environment alone would not have caused corrosion.
- **stress-corrosion cracking (SCC)**
    - A cracking process that requires the simultaneous action of a corrodent and sustained tensile stress. This excludes corrosion-reduced sections that fail by fast fracture. It also excludes intercrystalline or transcrystalline corrosion, which can disintegrate an alloy without applied or residual stress. Stress-corrosion cracking may occur in combination with hydrogen embrittlement.
- **stress-intensity factor**
    - A scaling factor, usually denoted by the symbol *K*, used in linear-elastic fracture mechanics to describe the intensification of applied stress at the tip of a crack of known size and shape. At the onset of rapid crack propagation in any structure containing a crack, the factor is called the critical stress-intensity factor, or the fracture toughness. Various subscripts are used to denote different loading conditions or fracture toughnesses:

K_c	Plane-stress fracture toughness. The value of stress intensity at which crack propagation becomes rapid in sections thinner than those in which plane-strain conditions prevail.
K_I	Stress-intensity factor for a loading condition that displaces the crack faces in a direction normal to the crack plane (also known as the opening mode of deformation).

K_{Ic}	Plane-strain fracture toughness. The minimum value of K_c for any given material and condition
K_{Id}	Dynamic fracture toughness. The fracture toughness determined under dynamic loading conditions; it is used as an approximation of K_{Ic} for very tough materials.
K_{Iscc}	Threshold stress-intensity factor for stress-corrosion cracking. The critical plane-strain stress intensity at the onset of stress-corrosion cracking under specified conditions.
K_Q	Provisional value for plane-strain fracture toughness.
K_{th}	Threshold stress intensity for stress-corrosion cracking. The critical stress intensity at the onset of stress-corrosion cracking under specified conditions.
ΔK	The range of the stress-intensity factor during a fatigue cycle. See also fatigue crack growth rate .

- **stress-intensity factor range (ΔK)**
  - In fatigue, the variation in the stress-intensity factor in a cycle, that is, $K_{max} - K_{min}$. See also fatigue crack growth rate .
- **stress raisers**
  - Design features (such as sharp corners) or mechanical defects (such as notches) that act to intensify the stress at these locations.
- **stress range**
  - See range of stress .
- **stress ratio (A or R)**
  - The algebraic ratio of two specified stress values in a stress cycle. Two commonly used stress ratios are: (1) the ratio of the alternating stress amplitude to the mean stress, $A = S_a/S_m$; and (2) the ratio of the minimum stress to the maximum stress, $R = S_{min}/S_{max}$.
- **stress relaxation**
  - The time-dependent decrease in stress in a solid under constant constraint at constant temperature.
- **stress-relaxation curve**
  - A plot of the remaining or relaxed stress as a function of time. The relaxed stress equals the initial stress minus the remaining stress. Also known as stress-time curve.
- **stress-relief cracking**
  - Cracking in the heat-affected zone or weld metal that occurs during the exposure of weldments to elevated temperatures during postweld heat treatment, in order to reduce residual stresses and improve toughness, or high-temperature service.
- **stress-relief heat treatment**
  - Uniform heating of a structure or a portion thereof to a sufficient temperature to relieve the major portion of the residual stresses, followed by uniform cooling.
- **stress relieving**
  - Heating to a suitable temperature, holding long enough to reduce residual stresses, and then cooling slowly enough to minimize the development of new residual stresses.
- **stress-rupture strength**
  - See creep-rupture strength .
- **stress-rupture test**
  - See creep-rupture test .
- **stress state**
  - See state of stress .
- **stress-strain curve**
  - A graph in which corresponding values of stress and strain from a tension, compression, or torsion test are plotted against each other. Values of stress are usually plotted vertically (ordinates or y-axis) and values of strain horizontally (abscissas or x-axis). Also known as deformation curve and stress-strain diagram.
- **stretcher leveling**
  - The leveling of a piece of sheet metal (that is, removing warp and distortion) by gripping it at both ends and subjecting it to a stress higher than its yield strength.
- **stretcher straightening**
  - A process for straightening rod, tubing, and shapes by the application of tension at the ends of the stock. The products are elongated a definite amount to remove warpage.
- **stretcher strains**

  - Elongated markings that appear on the surface of some sheet materials when deformed just past the yield point. These markings lie approximately parallel to the direction of maximum shear stress and are the result of localized yielding. See also Lüders lines .
- **stretch former**
  - (1) A machine used to perform stretch forming operations. (2) A device adaptable to a conventional press for accomplishing stretch forming.
- **stretch forming**
  - The shaping of a metal sheet or part, usually of uniform cross section, by first applying suitable tension or stretch and then wrapping it around a die of the desired shape.
- **stretching**
  - The extension of the surface of a metal sheet in all directions. In stretching, the flange of the flat blank is securely clamped. Deformation is restricted to the area initially within the die. The stretching limit is the onset of metal failure.
- **striation**
  - A fatigue fracture feature, often observed in electron micrographs, that indicates the position of the crack front after each succeeding cycle of stress. The distance between striations indicates the advance of the crack front across that crystal during one stress cycle, and a line normal to the striations indicates the direction of local crack propagation. See also beach marks .
- **strike**
  - (1) A thin electrodeposited film of metal to be overlaid with other plated coatings. (2) A plating solution of high covering power and low efficiency designed to electroplate a thin, adherent film of metal.
- **striking**
  - Electrodepositing, under special conditions, a very thin film of metal that will facilitate further plating with another metal or with the same metal under different conditions.
- **striking surface**
  - Those areas on the faces of a set of metalforming dies that are designed to meet when the upper die and lower die are brought together. The striking surface helps protect impressions from impact shock and aids in maintaining longer die life.
- **stringer**
  - In wrought materials, an elongated configuration of microconstituents or foreign material aligned in the direction of working. The term is commonly associated with elongated oxide or sulfide inclusions in steel.
- **stringer bead**
  - A continuous weld bead made without appreciable transverse oscillation (weaving motion). Contrast with weave bead .
- **strip**
  - (1) A flat-rolled metal product of some maximum thickness and width arbitrarily dependent on the type of metal; narrower than sheet. (2) A roll-compacted metal powder product. See also roll compacting . (3) Removal of a powder metallurgy compact from the die. An alternative to ejecting or knockout.
- **stripper**
  - A plate designed to remove, or strip, sheet metal stock from the punching members during the withdrawal cycle. Strippers are also used to guide small precision punches in close-tolerance dies to guide scrap away from dies and to assist in the cutting action. Strippers are made in two types: fixed and movable.
- **stripper punch**
  - A punch that serves as the top or bottom of a metalforming die cavity and later moves farther into the die to eject the part or compact. See also ejector rod and knockout(3) .
- **stripping**
  - (1) Removing a coating from a metal surface. (2) Removing a foundry pattern from the mold or the core box from the core.
- **structural shape**
  - A piece of metal of any of several designs accepted as standard by the structural branch of the iron and steel industries.
- **structure**

    - As applied to a crystal, the shape and size of the unit cell and the location of all atoms within the unit cell. As applied to microstructure, the size, shape, and arrangement of phases. See also unit cell .
- **stud arc welding**
    - An arc welding process that produces coalescence of metals by heating them with an arc between a metal stud, or similar part, and the other workpiece. When the surfaces to be joined are properly heated, they are brought together under pressure. Partial shielding may be obtained by the use of a ceramic ferrule surrounding the stud. Shielding gas or flux may or may not be used.
- **stud welding**
    - A general term for joining a metal stud or similar part to a workpiece. Welding may be accommodated by arc, resistance, friction, or other processes with or without external gas shielding.
- **styrofoam pattern**
    - An expendable pattern of foamed plastic, especially expanded polystyrene, used in manufacturing castings by the lost foam process. See also lost foam casting .
- **subboundary structure (subgrain structure)**
    - A network or low-angle boundaries, usually with misorientations less that 1° within the main grains of a microstructure.
- **subcritical annealing**
    - An annealing treatment in which a steel is heated to a temperature below the A_1 temperature, then cooled slowly to room temperature. See also transformation temperature .
- **subgrain**
    - A portion of a crystal or grain, with an orientation slightly different from the orientation of neighboring portions of the same crystal.
- **submerged arc welding (SAW)**
    - An arc welding process that produces coalescence of metals by heating them with an arc or arcs between a bare metal electrode or electrodes and the workpieces. The arc and molten metal are shielded by a blanket of granular, fusible material on the workpieces. Pressure is not used, and filler metal is obtained from the electrode and sometimes from a supplemental source (welding rod, flux, or metal granules).
- **submerged-electrode furnace**
    - A furnace used for liquid carburizing of parts by heating molten salt baths with the use of electrodes submerged in the ceramic lining. See also immersed-electrode furnace .
- **subsieve fraction**
    - Particles that will pass through a 44 μm (325 mesh) screen.
- **subsieve size**
    - See preferred term subsieve fraction .
- **substitutional element**
    - An alloying element with an atomic size and other features similar to the solvent that can replace or substitute for the solvent atoms in the lattice and form a significant region of solid solution in the phase diagram.
- **substitutional solid solution**
    - A solid solution in which the solvent and solute atoms are located randomly at the atom sites in the crystal structure of the solution. See also interstitial solid solution .
- **substrate**
    - The material, workpiece, or substance on which the coating is deposited.
- **substructure**
    - Same as subboundary structure .
- **subsurface corrosion**
    - Formation of isolated particles of corrosion products beneath a metal surface. This results from the preferential reactions of certain alloy constituents to inward diffusion of oxygen, nitrogen, or sulfur.
- **sulfidation**
    - The reaction of a metal or alloy with a sulfur-containing species to produce a sulfur compound that forms on or beneath the surface on the metal or alloy.
- **sulfide stress cracking (SSC)**
    - Brittle fracture by cracking under the combined action of tensile stress and corrosion in the presence of water and hydrogen sulfide. See also environmental cracking .

- **sulfur dome**
  - An inverted container, holding a high concentration of sulfur dioxide gas, used in die casting to cover a pot of molten magnesium to prevent burning.
- **sulfur print**
  - A macrographic method of examining for distribution of sulfide inclusions by placing a sheet of wet acidified photographic paper in contact with the polished sheet surface to be examined.
- **superabrasives**
  - Synthetically produced diamond and cubic boron nitride (CBN) used in a wide variety of cutting and grinding applications.
- **superalloys**
  - Heat-resistant alloys based on nickel, iron-nickel, or cobalt that exhibit high strength and resistance to surface degradation at elevated temperatures.
- **superconductivity**
  - A property of many metals, alloys, compounds, oxides, and organic materials at temperatures near absolute zero by virtue of which their electrical resistivity vanishes and they become strongly diamagnetic.
- **supercooling**
  - Cooling of a substance below the temperature at which a change of state would ordinarily take place without such a change of state occurring, for example, the cooling of a liquid below its freezing point without freezing taking place; this results in a metastable state.
- **superficial hardness test**
  - See Rockwell superficial hardness test .
- **superfines**
  - The portion of a metal powder that is composed of particles smaller than a specified size, usually 10 μm.
- **superfinishing**
  - A low-velocity abrading process very similar to honing; however, unlike honing, superfinishing processes focus primarily on the improvement of surface finish and much less on correction of geometric errors (dimensional accuracy). Also known as microhoning.
- **superheating**
  - (1) Heating of a substance above the temperature at which a change of state would ordinarily take place without a change of state occurring, for example, the heating of a liquid above its boiling point without boiling taking place; this results in a metastable state. (2) Any increment of temperature above the melting point of a metal; sometimes construed to be any increment of temperature above normal casting temperatures introduced for the purpose of refining, alloying, or improving fluidity.
- **superlattice**
  - See ordered structure .
- **superplastic forming (SPF)**
  - A strain rate sensitive sheet metal forming process that uses characteristics of materials exhibiting high tensile elongation. During superplastic forming, gas pressure is imposed on a superplastic sheet, causing the material to form into the die configuration. See also superplasticity .
- **superplasticity**
  - The ability of certain metals (most notably aluminum- and titanium-base alloys) to develop extremely high tensile elongations at elevated temperatures and under controlled rates of deformation.
- **supersaturated**
  - A metastable solution in which the dissolved material exceeds the amount the solvent can hold in normal equilibrium at the temperature and other conditions that prevail.
- **support pins**
  - Rods or pins of precise length used to support the overhang of irregularly shaped punches in metal forming presses.
- **support plate**
  - A plate that supports a draw ring or draw plate in a sheet metal forming press. It also serves as a spacer. See also draw plate and draw ring .
- **surface alterations**
  - Irregularities or changes on the surface of a material due to machining or grinding operations. The types of surface alterations associated with metal removal practices include mechanical (for

example, plastic deformation, hardness variations, cracks, etc.), metallurgical (for example, phase transformations, twinning, recrystallization, and untempered or overtempered martensite), chemical (for example, intergranular attack, embrittlement, and pitting), thermal (heat-affected zone, recast, or redeposited metal, and resolidified material), and electrical surface alterations (conductivity change or resistive heating).

- **surface checking**
  - Same as checks .
- **surface damage**
  - In tribology, damage to a solid surface resulting from mechanical contact with another substance, surface, or surfaces moving relatively to it and involving the displacement or removal of material. In certain contexts, wear is a form of surface damage in which material is progressively removed. In another context, surface damage involves a deterioration of function of a solid surface even though there is no material loss from that surface. Surface damage may therefore precede wear.
- **surface finish**
  - (1) The geometric irregularities in the surface of a solid material. Measurement of surface finish shall not include inherent structural irregularities unless these are the characteristics being measured. (2) Condition of a surface as a result of a final treatment. See also roughness .
- **surface grinding**
  - Producing a plane surface by grinding.
- **surface hardening**
  - A generic term covering several processes applicable to a suitable ferrous alloy that produces, by quench hardening only, a surface layer that is harder or more wear resistant than the core. There is no significant alteration of the chemical composition of the surface layer. The processes commonly used are carbonitriding, carburizing, induction hardening, flame hardening, nitriding, and nitrocarburizing. Use of the applicable specific process name is preferred.
- **surface modification**
  - The alteration of surface composition or structure by the use of energy or particle beams. Two types of surface modification methods commonly employed are ion implantation and laser surface processing.
- **surface roughness**
  - Fine irregularities in the surface texture of a material, usually including those resulting from the inherent action of the production process. Surface roughness is usually reported as the arithmetic roughness average, R_a, and is given in micrometers or microinches.
- **surface texture**
  - The roughness, waviness, lay, and flaws associated with a surface. See also lay .
- **surfacing**
  - The deposition of filler metal (material) on a base metal (substrate) to obtain desired properties or dimensions, as opposed to making a joint. See also buildup , buttering , cladding , coating , and hardfacing .
- **surfacing weld**
  - A type of weld composed of one or more stringer or weave beads deposited on an unbroken surface to obtain desired properties or dimensions.
- **swage**
  - (1) The operation of reducing or changing the cross-sectional area of stock by the fast impact of revolving dies. (2) The tapering of bar, rod, wire, or tubing by forging, hammering, or squeezing; reducing a section by progressively tapering lengthwise until the entire section attains the smaller dimension of the taper.
- **swaging**
  - Tapering bar, rod, wire, or tubing by forging, hammering, or squeezing; reducing a section by progressively tapering lengthwise until the entire section attains the smaller dimension of the taper. See also rotary swaging .
- **swarf**
  - Intimate mixture of grinding chips and fine particles of abrasive and bond resulting from a grinding operation.
- **sweat soldering**
  - A soldering process variation in which two or more parts that have been precoated with solder are reheated and assembled into a joint without the use of additional solder.

- **sweep**
  - A type of foundry pattern that is a template cut to the profile of the desired mold shape that, when revolved around a stake or spindle, produces that shape in the mold.
- **Swift cup test**
  - A simulative test for determining formability of sheet metal in which circular blanks of various diameters are clamped in a die ring and deep drawn into a cup by a flat-bottomed cylindrical punch. The ratio of the largest blank diameter that can be drawn successfully to the cup diameter is known as the limiting drawing ratio (LDR) or deformation limit.
- **swing forging machine**
  - Equipment for continuously hot reducing ingots, blooms, or billets to square flats, rounds, or rectangles by the crank-driven oscillating action of paired dies.
- **swing frame grinder**
  - A grinding machine suspended by a chain at the center point so that it may be turned and swung in any direction for grinding of billets, large castings, or other heavy work. Principal use is removing surface imperfections and roughness.
- **synthetic cold-rolled sheet**
  - A hot-rolled pickled sheet given a sufficient final temper pass to impart a surface approximating that of cold-rolled steel.
- **T**
- **tacking**
  - Making tack welds.
- **tack weld**
  - A weld made to hold parts of a weldment in proper alignment until the final welds are made.
- **tailings**
  - The discarded portion of a crushed ore, separated during concentration.
- **tandem mill**
  - A rolling mill consisting of two or more stands arranged so that the metal being processed travels in a straight line from stand to stand. In continuous rolling, the various stands are synchronized so that the strip can be rolled in all stands simultaneously. Contrast with single-stand mill . See also rolling mills .
- **tandem welding**
  - Arc welding in which two or more electrodes are in a plane parallel to the line of travel.
- **tangent bending**
  - The forming of one or more identical bends having parallel axes by wiping sheet metal around one or more radius dies in a single operation. The sheet, which may have side flanges, is clamped against the radius die and then made to conform to the radius die by pressure from a rocker-plate die that moves along the periphery of the radius die. See also wiper forming (wiping) .
- **tap**
  - A cylindrical or conical thread-cutting tool with one or more cutting elements having threads of a desired form on the periphery. By a combination of rotary and axial motions, the leading end cuts an internal thread, the tool deriving its principal support from the thread being produced.
- **tap density**
  - The apparent density of a powder, obtained when the volume receptacle is tapped or vibrated during loading under specified conditions.
- **tapping**
  - (1) Producing internal threads with a cylindrical cutting tool having two or more peripheral cutting elements shaped to cut threads of the desired size and form. By a combination of rotary and axial motion, the leading end of the tap cuts the thread while the tap is supported mainly by the thread it produces. See also tap . (2) Opening the outlet of a melting furnace to remove molten metal. (3) Removing molten metal from a furnace.
- **tarnish**
  - Surface discoloration of a metal caused by formation of a thin film of corrosion product.
- **teapot ladle**
  - A ladle in which, by means of an external spout, metal is removed from the bottom rather than the top of the ladle.
- **teeming**
  - Pouring molten metal from a ladle into ingot molds. The term applies particularly to the specific operation of pouring either iron or steel into ingot molds.

- **temper**
    - (1) In heat treatment, reheating hardened steel or hardened cast iron to some temperature below the eutectoid temperature for the purpose of decreasing hardness and increasing toughness. The process also is sometimes applied to normalized steel. (2) In tool steels, temper is sometimes used, but inadvisedly, to denote the carbon content. (3) In nonferrous alloys and in some ferrous alloys (steels that cannot be hardened by heat treatment), the hardness and strength produced by mechanical or thermal treatment, or both, and characterized by a certain structure, mechanical properties, or reduction in area during cold working. (4) To moisten green sand for casting molds with water.
- **temper brittleness**
    - See temper embrittlement .
- **temper carbon**
    - Clusters of finely divided graphite, such as that found in malleable iron, that are formed as a result of decomposition of cementite, for example, by heating white cast iron above the ferrite-austenite transformation temperature and holding at these temperatures for a considerable period of time. Also known as annealing carbon.
- **temper color**
    - A thin, tightly adhering oxide skin (only a few molecules thick) that forms when steel is tempered at a low temperature, or for a short time, in air or a mildly oxidizing atmosphere. The color, which ranges from straw to blue depending on the thickness of the oxide skin, varies with both tempering time and temperature.
- **tempered layer**
    - A surface or subsurface layer in a steel specimen that has been tempered by heating during some stage of the metallographic preparation sequence (usually grinding). When observed in a section after etching, the layer appears darker than the base material.
- **tempered martensite**
    - The decomposition products that result from heating martensite below the ferrite-austenite transformation temperature.
- **tempered martensite embrittlement**
    - Embrittlement of high-strength alloy steels caused by tempering in the temperature range of 205 to 370 °C (400 to 700 °F); also called 350 °C or 500 °F embrittlement. Tempered martensite embrittlement is thought to result from the combined effects of cementite precipitation on prior-austenite grain boundaries or interlath boundaries and the segregation of impurities at prior-austenite grain boundaries. It differs from temper embrittlement in the strength of the material and the temperature exposure range. In temper embrittlement, the steel is usually tempered at a relatively high temperature, producing lower strength and hardness, and embrittlement occurs upon slow cooling after tempering and during service at temperatures within the embrittlement range. In tempered martensite embrittlement, the steel is tempered within the embrittlement range, and service exposure is usually at room temperature.
- **temper embrittlement**
    - Embrittlement of low-alloy steels caused by holding within or cooling slowly through a temperature range (generally 300 to 600 °C, or 570 to 1110 °F) just below the transformation range. Embrittlement is the result of the segregation at grain boundaries of impurities such as arsenic, antimony, phosphorus, and tin; it is usually manifested as an upward shift in ductile-to-brittle transition temperature. Temper embrittlement can be reversed by retempering above the critical temperature range, then cooling rapidly. Compare with tempered martensite embrittlement .
- **tempering**
    - In heat treatment, reheating hardened steel to some temperature below the eutectoid temperature to decrease hardness and/or increase toughness.
- **temper rolling**
    - Light cold rolling of sheet steel to improve flatness, to minimize the formation of stretcher strains, and to obtain a specified hardness or temper.
- **tensile strength**
    - In tensile testing, the ratio of maximum load to original cross-sectional area. Also called ultimate strength . Compare with yield strength .
- **tensile stress**

    - A stress that causes two parts of an elastic body, on either side of a typical stress plane, to pull apart. Contrast with compressive stress .
- **tensile testing**
    - See tension testing .
- **tension**
    - The force or load that produces elongation.
- **tension testing**
    - A method of determining the behavior of materials subjected to uniaxial loading, which tends to stretch the material. A longitudinal specimen of known length and diameter is gripped at both ends and stretched at a slow, controlled rate until rupture occurs. Also known as tensile testing.
- **terminal phase**
    - A solid solution having a restricted range of compositions, one end of the range being a pure component of an alloy system.
- **terminal solid solution**
    - In a multicomponent system, any solid phase of limited composition range that includes the composition of one of the components of the system. See also solid solution .
- **ternary alloy**
    - An alloy that contains three principal elements.
- **ternary system**
    - The complete series of compositions produced by mixing three components in all proportions.
- **terne**
    - An alloy of lead containing 3 to 15% Sn, used as a hot dip coating for steel sheet or plate. The term long terne is used to describe terne-coated sheet, whereas short terne is used for terne-coated plate. Terne coatings, which are smooth and dull in appearance (terne means dull or tarnished in French), give the steel better corrosion resistance and enhance its ability to be formed, soldered, or painted.
- **tertiary creep**
    - See creep .
- **texture**
    - In a polycrystalline aggregate, the state of distribution of crystal orientations. In the usual sense, it is synonymous with preferred orientation , in which the distribution is not random. Not to be confused with surface texture . See also fiber .
- **thermal aging**
    - Exposure of a material or component to a given thermal condition or a programmed series of conditions for prescribed periods of time.
- **thermal analysis**
    - A method for determining transformations in a metal by noting the temperatures at which thermal arrests occur. These arrests are manifested by changes in slope of the plotted or mechanically traced heating and cooling curves. When such data are secured under nearly equilibrium conditions of heating and cooling, the method is commonly used for determining certain critical temperatures required for the construction of phase diagrams.
- **thermal cutting**
    - A group of cutting processes that melts the metal (material) to be cut. See also air carbon arc cutting , arc cutting , carbon arc cutting , electron beam cutting , laser beam cutting , metal powder cutting , oxyfuel gas cutting , oxygen arc cutting , oxygen cutting , and plasma arc cutting .
- **thermal decomposition**
    - (1) The decomposition of a compound into its elemental species at elevated temperatures. (2) A process whereby fine solid particles can be produced from a gaseous compound. See also carbonyl powder .
- **thermal electromotive force**
    - The electromotive force generated in a circuit containing two dissimilar metals when one junction is at a temperature different from that of the other. See also thermocouple .
- **thermal embrittlement**
    - Intergranular fracture of maraging steels with decreased toughness resulting from improper processing after hot working. Thermal embrittlement occurs upon heating above 1095 °C (2000 °F) and then slow cooling through the temperature range of 980 to 815 °C (1800 to 1500 °F), and

    has been attributed to precipitation of titanium carbides and titanium carbonitrides at austenite grain boundaries during cooling through the critical temperature range.

- **thermal fatigue**
  - Fracture resulting from the presence of temperature gradients that vary with time in such a manner as to produce cyclic stresses in a structure.
- **thermal inspection**
  - A nondestructive test method in which heat-sensing devices are used to measure temperature variations in components, structures, systems, or physical processes. Thermal methods can be useful in the detection of subsurface flaws or voids, provided the depth of the flaw is not large compared to its diameter. Thermal inspection becomes less effective in the detection of subsurface flaws as the thickness of an object increases, because the possible depth of the defects increases.
- **thermally induced embrittlement**
  - See embrittlement .
- **thermal-mechanical treatment**
  - See thermomechanical working .
- **thermal shock**
  - The development of a steep temperature gradient and accompanying high stresses within a material or structure.
- **thermal spraying**
  - A group of coating or welding processes in which finely divided metallic or nonmetallic materials are deposited in a molten or semimolten condition to form a coating. The surfacing material may be in the form of powder, rod, or wire. See also electric arc spraying , flame spraying , plasma spraying , and powder flame spraying .
- **thermal stresses**
  - Stresses in a material resulting from nonuniform temperature distribution.
- **thermal wear**
  - Removal of material due to softening, melting, or evaporation during sliding or rolling. Thermal shock and high-temperature erosion may be included in the general description of thermal wear. Wear by diffusion of separate atoms from one body to the other, at high temperatures, is also sometimes denoted as thermal wear.
- **thermit reactions**
  - Strongly exothermic self-propagating reactions such as that where finely divided aluminum reacts with a metal oxide. A mixture of aluminum and iron oxide produces sufficient heat to weld steel, the filler metal being produced in the reaction. See also thermit welding .
- **thermit welding**
  - A welding process that produces coalescence of metals by heating them with superheated liquid metal from a chemical reaction between a metal oxide and aluminum, with or without the application of pressure. Filler metal is obtained from the liquid metal.
- **thermochemical machining**
  - Removal of workpiece material--usually only burrs and fins--by exposure to hot fuel gases that are formed by igniting an explosive, combustible mixture of natural gas and oxygen. Also known as the thermal energy method.
- **thermochemical treatment**
  - Heat treatment for steels carried out in a medium suitably chosen to produce a change in the chemical composition of the object by exchange with the medium.
- **thermocouple**
  - A device for measuring temperatures, consisting of lengths of two dissimilar metals or alloys that are electrically joined at one end and connected to a voltage-measuring instrument at the other end. When one junction is hotter than the other, a thermal electromotive force is produced that is roughly proportional to the difference in temperature between the hot and cold junctions.
- **thermomechanical working**
  - A general term covering a variety of metalforming processes combining controlled thermal and deformation treatments to obtain synergistic effects, such as improvement in strength without loss of toughness. Same as thermal-mechanical treatment.
- **thief**
  - A racking device or nonfunctional pattern area used in the electroplating process to provide a more uniform current density on plated parts. Thieves absorb the unevenly distributed current on

  irregularly shaped parts, thereby ensuring that the parts will receive an electroplated coating of uniform thickness. See also robber .

- **thin-wall casting**
  - A term used to define a casting that has the minimum wall thickness to satisfy its service function.
- **threading**
  - Producing external threads on a cylindrical surface.
- **thread rolling**
  - The production of threads by rolling the piece between two grooved die plates, one of which is in motion, or between rotating grooved circular rolls. Also known as roll threading.
- **three-quarters hard**
  - A temper of nonferrous alloys and some ferrous alloys characterized by tensile strength and hardness about midway between those of half hard and full hard tempers.
- **three-point bending**
  - The bending of a piece of metal or a structural member in which the object is placed across two supports and force is applied between and in opposition to them. See also V-bend die .
- **threshold stress**
  - Threshold stress for stress-corrosion cracking. The critical gross section stress at the onset of stress-corrosion cracking under specified conditions.
- **throwing power**
  - (1) The relationship between the current density at a point on a surface and its distance from the counterelectrode. The greater the ratio of the surface resistivity shown by the electrode reaction to the volume resistivity of the electrolyte, the better is the throwing power of the process. (2) The ability of a plating solution to produce a uniform metal distribution on an irregularly shaped cathode. Compare with covering power .
- **tiger stripes**
  - Continuous bright lines on sheet or strip in the rolling direction.
- **TIG welding**
  - Tungsten inert-gas welding; see preferred term gas tungsten arc welding .
- **tilt boundary**
  - A subgrain boundary consisting of an array of edge dislocations.
- **tilt mold**
  - A casting mold, usually a book (permanent) mold, that rotates from a horizontal to a vertical position during pouring, which reduces agitation and thus the formation and entrapment of oxides.
- **tilt mold ingot**
  - An ingot made in a tilt mold .
- **time quenching**
  - A quench in which the cooling rate of the part being quenched must be changed abruptly at some time during the cooling cycle.
- **time-temperature curve**
  - A curve produced by plotting time against temperature.
- **time-temperature-transformation (TTT) diagram**
  - See isothermal transformation (IT) diagram .
- **tinning**
  - Coating metal with a very thin layer of molten solder or brazing filler metal.
- **tin pest**
  - A polymorphic modification of tin that causes it to crumble into a powder known as gray tin. It is generally accepted that the maximum rate of transformation occurs at about -40 °C (-40 °F), but transformation can occur at as high as about 13 °C (55 °F).
- **tint etching**
  - Immersing metallographic specimens in specially formulated chemical etchants in order to produce a stable film on the specimen surface. When viewed under an optical microscope, these surface films produce colors that correspond to the various phases in the alloy. Also known as color etching.
- **tin tossing**
  - Oxidizing impurities in molten tin by pouring it from one vessel to another in air, forming a dross that is mechanically separable.

- **toggle press**
  - A mechanical press in which the slide is actuated by one or more toggle links or mechanisms.
- **tolerance**
  - The specified permissible deviation from a specified nominal dimension, or the permissible variation in size or other quality characteristic of a part.
- **tolerance limits**
  - The extreme values (upper and lower) that define the range of permissible variation in size or other quality characteristic of a part.
- **tonghold**
  - The portion of a forging billet, usually on one end, that is gripped by the operator's tongs. It is removed from the part at the end of the forging operation. Common to drop hammer and press-type forging.
- **tooling**
  - A generic term applying to die assemblies and related items used for forming and forging metals.
- **tool steel**
  - Any of a class of carbon and alloy steels commonly used to make tools. Tool steels are characterized by high hardness and resistance to abrasion, often accompanied by high toughness and resistance to softening at elevated temperature. These attributes are generally attained with high carbon and alloy contents.
- **tooth**
  - (1) A projection on a multipoint tool (such as on a saw, milling cutter, or file) designed to produce cutting. (2) A projection on the periphery of a wheel or segment thereof--as on a gear, spline, or sprocket, for example--designed to engage another mechanism and thereby transmit force or motion, or both. A similar projection on a flat member such as a rack.
- **tooth point**
  - The chamfered cutting edge of a face milling blade, to which a flat is sometimes added to produce a shaving effect and to improve finish.
- **top-and-bottom process**
  - A process for separating copper and nickel, in which their molten sulfides are separated into two liquid layers by the addition of sodium sulfide. The lower layer holds most of the nickel.
- **torch**
  - See preferred terms cutting torch (arc) , cutting torch (oxyfuel gas) , welding torch (arc) , and welding torch (oxyfuel gas) .
- **torch brazing**
  - A brazing process in which the heat required is furnished by a fuel gas flame.
- **torch soldering**
  - A soldering process in which the heat required is furnished by a fuel gas flame.
- **torsion**
  - (1) A twisting deformation of a solid or tubular body about an axis in which lines that were initially parallel to the axis become helices. (2) A twisting action resulting in shear stresses and strains.
- **torsional moment**
  - In a body being twisted, the algebraic sum of the couples or the moments of the external forces about the axis of twist, or both.
- **total carbon**
  - The sum of the free carbon and combined carbon (including carbon in solution) in a ferrous alloy.
- **total elongation**
  - The total amount of permanent extension of a test piece broken in a tensile test usually expressed as a percentage over a fixed gage length. See also elongation, percent .
- **toughness**
  - Ability of a material to absorb energy and deform plastically before fracturing. Toughness is proportional to the area under the stress-strain curve from the origin to the breaking point. In metals, toughness is usually measured by the energy absorbed in a notch impact test. See also impact test .
- **tough pitch copper**
  - Copper containing from 0.02 to 0.04% O, obtained by refining copper in a reverberatory furnace.
- **tracer milling**

  - Duplication of a three-dimensional form by means of a cutter controlled by a tracer that is directed by a master form.
- **tramp alloys**
  - Residual alloying elements that are introduced into steel when unidentified alloy steel is present in the scrap charge to a steelmaking furnace.
- **tramp element**
  - Contaminant in the components of a furnace charge, or in the molten metal or castings, whose presence is thought to be either unimportant or undesirable to the quality of the casting. Also called trace element.
- **transcrystalline**
  - See transgranular .
- **transcrystalline cracking**
  - Cracking or fracturing that occurs through or across a crystal. Also termed intracrystalline cracking.
- **transformation hardening**
  - Heat treatment of steels comprising austenitization followed by cooling under conditions such that the austenite transforms more or less completely into martensite and possibly into bainite.
- **transformation-induced plasticity**
  - A phenomenon, occurring chiefly in certain highly alloyed steels that have been heat treated to produce metastable austenite or metastable austenite plus martensite, whereby, on subsequent deformation, part of the austenite undergoes strain-induced transformation to martensite. Steels capable of transforming in this manner, commonly referred to as TRIP steels, are highly plastic after heat treatment, but exhibit a very high rate of strain hardening and thus have high tensile and yield strengths after plastic deformation at temperatures between about 20 and 500 °C (70 and 930 °F). Cooling to 195 °C (320 °F) may or may not be required to complete the transformation to martensite. Tempering usually is done following transformation.
- **transformation ranges**
  - Those ranges of temperature within which austenite forms during heating and transforms during cooling. The two ranges are distinct, sometimes overlapping but never coinciding. The limiting temperatures of the ranges depend on the composition of the alloy and on the rate of change of temperature, particularly during cooling. See also transformation temperature .
- **transformation temperature**
  - The temperature at which a change in phase occurs. This term is sometimes used to denote the limiting temperature of a transformation range. The following symbols are used for irons and steels:

Ac_{cm}	In hypereutectoid steel
Ac_1	The temperature at which austenite begins to form during heating.
Ac_3	The temperature at which transformation of ferrite to austenite is completed during heating.
Ac_4	The temperature at which austenite transforms to δ ferrite during heating.
Ae_{cm}, Ae_1, Ae_3, Ae_4	The temperatures of phase changes at equilibrium
Ar_{cm}	In hypereutectoid steel
Ar_1	The temperature at which transformation of austenite to ferrite or to ferrite plus cementite is completed during cooling.
Ar_3	The temperature at which austenite begins to transform to ferrite during cooling.
Ar_4	The temperature at which δ ferrite transforms to austenite during cooling.
Ar'	The temperature at which transformation of austenite to pearlite starts during cooling.
M_f	The temperature at which transformation of austenite to martensite is completed during cooling.
M_s(or Ar'')	The temperature at which transformation of austenite to martensite starts during cooling.

    - NOTE: All these changes, except formation of martensite, occur at lower temperatures during cooling than during heating, and depend on the rate of change of temperature.
- **transgranular**
    - Through or across crystals or grains. Also called intracrystalline or transcrystalline.
- **transgranular cracking**
    - Cracking or fracturing that occurs through or across a crystal or grain. Also called transcrystalline cracking. Contrast with intergranular cracking .
- **transgranular fracture**
    - Fracture through or across the crystals or grains of a material. Also called transcrystalline fracture or intracrystalline fracture. Contrast with intergranular fracture .
- **transition lattice**
    - An unstable crystallographic configuration that forms as an intermediate step in a solid-state reaction such as precipitation from solid solution or eutectoid decomposition.
- **transition metal**
    - A metal in which the available electron energy levels are occupied in such a way that the ***d***-band contains less than its maximum number of ten electrons per atom, for example, iron, cobalt, nickel, and tungsten. The distinctive properties of the transition metals result from the incompletely filled ***d***-levels.
- **transition phase**
    - A nonequilibrium state that appears in a chemical system in the course of transformation between two equilibrium states.
- **transition point**
    - At a stated pressure, the temperature (or at a stated temperature, the pressure) at which two solid phases exist in equilibrium--that is, an allotropic transformation temperature (or pressure).
- **transition structure**
    - In precipitation from solid solution, a metastable precipitate that is coherent with the matrix.
- **transition temperature**
    - (1) An arbitrarily defined temperature that lies within the temperature range in which metal fracture characteristics (as usually determined by tests of notched specimens) change rapidly, such as the ductile-to-brittle transition temperature (DBTT). The DBTT can be assessed in several ways, the most common being the temperature for 50% ductile and 50% brittle fracture (50% fracture appearance transition temperature, or FATT), or the lowest temperature at which the fracture is 100% ductile (100% fibrous criterion). (2) Sometimes used to denote an arbitrarily defined temperature within a range in which the ductility changes rapidly with temperature.
- **transverse direction**
    - Literally, "across," usually signifying a direction or plane perpendicular to the direction of working. In rolled plate or sheet, the direction across the width is often called long transverse; the direction through the thickness, short transverse.
- **transverse rolling machine**
    - Equipment for producing complex preforms or finished forgings from round billets inserted transversely between two or three rolls that rotate in the same direction and drive the billet. The rolls, carrying replaceable die segments with appropriate impressions, make several revolutions for each rotation of the workpiece.
- **transverse rupture strength (TRS)**
    - The stress, calculated from the bending stress formula, required to break a powder metallurgy specimen of a given dimension. The specimen is supported near its ends with a load applied midway between the fixed centerline of the supports. From the value of the break load, the TRS can be calculated using:

$$\mathrm{TRS} = \frac{3FL}{WH^2}$$

    - where F is the load at fracture, L is the span between supports, and W and H are the width and height of the test bar, respectively.
- **trees**
    - Visible projections of electrodeposited metal formed at sites of high current density.
- **trepanning**

    - A machining process for producing a circular hole or groove in solid stock, or for producing a disk, cylinder, or tube from solid stock, by the action of a tool containing one or more cutters (usually single-point) revolving around a center.
- **triaxiality**
    - In a triaxial stress state, the ratio of the smallest to the largest principal stress, all stresses being tensile.
- **triaxial stress**
    - A state of stress in which none of the three principal stresses is zero. See also principal stress (normal) .
- **tribology**
    - (1) The science and technology of interacting surfaces in relative motion and of the practices related thereto. (2) The science concerned with the design, friction, lubrication, and wear of contacting surfaces that move relative to each other (as in bearings, cams, or gears, for example).
- **trimmer blade**
    - The portion of the trimmers through which a forging is pushed to shear off the flash.
- **trimmer die**
    - The punch press die used for trimming flash from a forging.
- **trimmer punch**
    - The upper portion of the trimmer that contacts the forging and pushes it through the trimmer blades; the lower end of the trimmer punch is generally shaped to fit the surface of the forging against which it pushes.
- **trimmers**
    - The combination of trimmer punch, trimmer blades, and perhaps trimming shoe used to remove the flash from the forging.
- **trimming**
    - (1) In forging, removing any parting-line flash or excess material from the part with a trimmer in a trim press; can be done hot or cold. (2) In drawing, shearing the irregular edge of the drawn part. (3) In casting, the removal of gates, risers, and fins.
- **trimming press**
    - A power press suitable for trimming flash from forgings.
- **trimming shoe**
    - The holder used to support trimmers. Sometimes called trimming chair.
- **triple-action press**
    - A mechanical or hydraulic press having three slides with three motions properly synchronized for triple-action drawing, redrawing, and forming. Usually, two slides--the blankholder slide and the plunger--are located above and a lower slide is located within the bed of the press. See also hydraulic press , mechanical press , and slide .
- **triple point**
    - (1) A point on a phase diagram where three phases of a substance coexist in equilibrium. (2) The intersection of the boundaries of three adjoining grains, as observed in a metallographic section.
- **TRIP steel**
    - A commercial steel product exhibiting transformation-induced plasticity .
- **troostite (obsolete)**
    - A previously unresolvable, rapidly etching, fine aggregate of carbide and ferrite produced either by tempering martensite at low temperature or by quenching a steel at a rate slower than the critical cooling rate. Preferred terminology for the first product is tempered martensite; for the latter, fine pearlite.
- **Troy ounce**
    - A unit of weight for precious metals that is equal to 31.1034768 g (1.0971699 oz avoirdupois).
- **true current density**
    - See preferred term local current density .
- **true strain**
    - (1) The ratio of the change in dimension, resulting from a given load increment, to the magnitude of the dimension immediately prior to applying the load increment. (2) In a body subjected to axial force, the natural logarithm of the ratio of the gage length at the moment of observation to the original gage length. Also known as natural strain.
- **true stress**

  - The value obtained by dividing the load applied to a member at a given instant by the cross-sectional area over which it acts.
- **truing**
  - The removal of the outside layer of abrasive grains on a grinding wheel for the purpose of restoring its face.
- **tuberculation**
  - The formation of localized corrosion products scattered over the surface in the form of knoblike mounds called tubercles. The formation of tubercles is usually associated with biological corrosion.
- **tube reducing**
  - Reducing both the diameter and wall thickness of tubing with a mandrel and a pair of rolls. See also spinning .
- **tube sinking**
  - Drawing tubing through a die or passing it through rolls without the use of an interior tool (such as a mandrel or plug) to control inside diameter; sinking generally produces a tube of increased wall thickness and length.
- **tube stock**
  - A semifinished tube suitable for subsequent reduction and finishing.
- **tumbling**
  - Rotating workpieces, usually castings or forgings, in a barrel partly filled with metal slugs or abrasives, to remove sand, scale, or fins. It may be done dry, or with an aqueous solution added to the contents of the barrel. See also barrel finishing .
- **Turk's-head rolls**
  - Four undriven working rolls, arranged in a square or rectangular pattern, through which metal strip, wire, or tubing is drawn to form square or rectangular sections.
- **turning**
  - Removing material by forcing a single-point cutting tool against the surface of a rotating workpiece. The tool may or may not be moved toward or along the axis of rotation while it cuts away material.
- **tuyere**
  - An opening in a cupola, blast furnace, or converter for the introduction of air or inert gas.
- **twin**
  - Two portions of a crystal with a definite orientation relationship; one may be regarded as the parent, the other as the twin. The orientation of the twin is a mirror image of the orientation of the parent across a twinning plane or an orientation that can be derived by rotating the twin portion about a twinning axis. See also annealing twin and mechanical twin .
- **twin bands**
  - Bands across a crystal grain, observed on a polished and etched section, where crystallographic orientations have a mirror-image relationship to the orientation of the matrix grain across a composition plane that is usually parallel to the sides of the band.
- **twist boundary**
  - A subgrain boundary consisting of an array of screw dislocations.
- **two-high mill**
  - A type of rolling mill in which only two rolls, the working rolls, are contained in a single housing. Compare with four-high mill and cluster mill.
- **type metal**
  - Any of a series of alloys containing lead (58.5 to 95%), antimony (2.5 to 25%), and tin (2.5 to 20%) used to make printing type. Small amounts of copper (1.5 to 2.0%) are added to increase hardness in some applications.
- **U**
- **U-bend die**
  - A die, commonly used in press-brake forming, that is machined horizontally with a square or rectangular cross-sectional opening that provides two edges over which metal is drawn into a channel shape.
- **Ugine-Sejournet process**
  - A direct extrusion process for metals that uses molten glass to insulate the hot billet and to act as a lubricant.
- **ultimate elongation**

    - The elongation at rupture.
- **ultimate strength**
    - The maximum stress (tensile, compressive, or shear) a material can sustain without fracture; determined by dividing maximum load by the original cross-sectional area of the specimen. Also known as nominal strength or maximum strength.
- **ultimate tensile strength**
    - The ultimate or final (highest) stress sustained by a specimen in a tension test.
- **ultrahard tool materials**
    - Very hard, wear-resistant materials--specifically, polycrystalline diamond and polycrystalline cubic boron nitride--that are fabricated into solid or layered cutting tool blanks for machining applications.
- **ultrahigh-strength steels**
    - Structural steels with minimum yield strengths of 1380 MPa (200 ksi).
- **ultraprecision finishing**
    - Machining processes used to alter surface characteristics such as finish, waviness, roundness, etc., with substantial removal of the work material. Examples include lapping and polishing of optical lenses, computer chips, or magnetic heads, and honing of cylinder liners.
- **ultrasonic beam**
    - A beam of acoustical radiation with a frequency higher than the frequency range for audible sound--i.e., above about 20 kHz.
- **ultrasonic cleaning**
    - Immersion cleaning aided by ultrasonic waves that cause microagitation.
- **ultrasonic frequency**
    - A frequency, associated with elastic waves, that is greater than the highest audible frequency, generally regarded as being higher than 20 kHz.
- **ultrasonic impact grinding**
    - A form of abrasive grinding in which a nonrotating tool vibrating at ultrasonic frequency causes a grit-loaded slurry to impinge on the surface of a workpiece, and thereby remove material. Compare with ultrasonic machining .
- **ultrasonic inspection**
    - A nondestructive method in which beams of high-frequency sound waves are introduced into materials for the detection of surface and subsurface flaws in the material. The sound waves travel through the material with some attendant loss of energy (attenuation) and are reflected at interfaces. The reflected beam is displayed and then analyzed to define the presence and location of flaws or discontinuities. Most ultrasonic inspection is done at frequencies between 0.1 and 25 MHz--well above the range of human hearing, which is about 20 Hz to 20 kHz.
- **ultrasonic machining**
    - Material removal by means of the ultrasonic vibration of a rotating diamond core drill or milling tool. The process does not involve an abrasive slurry; instead, the diamond tool contacts and cuts the workpiece. Compare with ultrasonic impact grinding .
- **ultrasonic soldering**
    - A soldering process variation in which high-frequency vibratory energy is transmitted through molten solder to remove undesirable surface films and thereby promote wetting of the base metal. This operation is usually accomplished without a flux.
- **ultrasonic testing**
    - See ultrasonic inspection .
- **ultrasonic welding**
    - A solid-state welding process in which materials are welded by locally applying high-frequency vibratory energy to a joint held together under pressure.
- **underbead crack**
    - A crack in the heat-affected zone of a weld generally not extending to the surface of the base metal.
- **undercooling**
    - Same as supercooling .
- **underdraft**
    - A condition wherein a metal curves downward on leaving a set of rolls because of higher speed in the upper roll.
- **underfill**

  - (1) In weldments, a depression on the face of the weld or root surface extending below the surface of the adjacent base metal. (2) A portion of a forging that has insufficient metal to give it the true shape of the impression.
- **underfilm corrosion**
  - Corrosion that occurs under organic films in the form of randomly distributed threadlike filaments or spots. In many cases this is identical to filiform corrosion .
- **understressing**
  - Applying a cyclic stress lower than the endurance limit. This may improve fatigue life if the member is later cyclically stressed at levels above the endurance limit.
- **uniaxial stress**
  - A state of stress in which two of the three principal stresses are zero. See also principal stress (normal) .
- **uniform corrosion**
  - (1) A type of corrosion attack (deterioration) uniformly distributed over a metal surface. (2) Corrosion that proceeds at approximately the same rate over a metal surface. Also called general corrosion.
- **uniform elongation**
  - The elongation at maximum load and immediately preceding the onset of necking in a tensile test.
- **uniform strain**
  - The strain occurring prior to the beginning of localization of strain (necking); the strain to maximum load in the tension test.
- **unit cell**
  - A parallelepiped element of crystal structure, containing a certain number of atoms, the repetition of which through space will build up the complete crystal.
- **unit power**
  - The net amount of power required during machining or grinding to remove a unit volume of material in unit time.
- **universal forging mill**
  - A combination of four hydraulic presses arranged in one plane equipped with billet manipulators and automatic controls, used for radial or draw forging.
- **universal mill**
  - A rolling mill in which rolls with a vertical axis roll the edges of the metal stock between some of the passes through the horizontal rolls.
- **upset**
  - (1) The localized increase in cross-sectional area of a workpiece or weldment resulting from the application of pressure during mechanical fabrication or welding. (2) That portion of a welding cycle during which the cross-sectional area is increased by the application of pressure. (3) Bulk deformation resulting from the application of pressure in welding. The upset may be measured as a percent increase in interfacial area, a reduction in length, or a percent reduction in thickness (for lap joints).
- **upset forging**
  - A forging obtained by upset of a suitable length of bar, billet, or bloom.
- **upsetting**
  - The working of metal so that the cross-sectional area of a portion or all of the stock is increased. See also heading .
- **upset welding**
  - A resistance welding process in which the weld is produced, simultaneously over the entire area of abutting surfaces or progressively along a joint, by applying mechanical force (pressure) to the joint, then causing electrical current to flow across the joint to heat the abutting surfaces. Pressure is maintained throughout the heating period.
- **V**
- **vacancy**
  - A structural imperfection in which an individual atom site is temporarily unoccupied.
- **vacuum arc remelting (VAR)**
  - A consumable-electrode remelting process in which heat is generated by an electric arc between the electrode and the ingot. The process is performed inside a vacuum chamber. Exposure of the droplets of molten metal to the reduced pressure reduces the amount of dissolved gas in the metal. See also consumable-electrode remelting .

- **vacuum carburizing**
    - A high-temperature gas carburizing process using furnace pressures between 13 and 67 kPa (0.1 to 0.5 torr) during the carburizing portion of the cycle. Steels undergoing this treatment are austenitized in a rough vacuum, carburized in a partial pressure of hydrocarbon gas, diffused in a rough vacuum, and then quenched in either oil or gas.
- **vacuum casting**
    - A casting process in which metal is melted and poured under very low atmospheric pressure; a form of permanent mold casting in which the mold is inserted into liquid metal, vacuum is applied, and metal is drawn up into the cavity.
- **vacuum degassing**
    - The use of vacuum techniques to remove dissolved gases from molten alloys.
- **vacuum deposition**
    - Deposition of a metal film onto a substrate in a vacuum by metal evaporation techniques.
- **vacuum furnace**
    - A furnace using low atmospheric pressures instead of a protective gas atmosphere like most heat-treating furnaces.
- **vacuum hot pressing**
    - A method of processing materials (especially metal and ceramic powders) at elevated temperatures, consolidation pressures, and low atmospheric pressures.
- **vacuum induction melting (VIM)**
    - A process for remelting and refining metals in which the metal is melted inside a vacuum chamber by induction heating. The metal can be melted in a crucible and then poured into a mold.
- **vacuum melting**
    - Melting in a vacuum to prevent contamination from air and to remove gases already dissolved in the metal; the solidification can also be carried out in a vacuum or at low pressure.
- **vacuum nitrocarburizing**
    - A subatmospheric nitrocarburizing process using a basic atmosphere of 50% ammonia/50% methane, containing controlled oxygen additions of up to 2%.
- **vacuum refining**
    - Melting in a vacuum to remove gaseous contaminants from the metal.
- **vacuum sintering**
    - Sintering of ceramics or metals at subatmospheric pressure.
- **vapor degreasing**
    - Degreasing of work in the vapor over a boiling liquid solvent, the vapor being considerably heavier than air. At least one constituent of the soil must be soluble in the solvent. Modifications of this cleaning process include vapor-spray-vapor, warm liquid-vapor, boiling liquid-warm liquid-vapor, and ultrasonic degreasing.
- **vapor deposition**
    - See chemical vapor deposition , physical vapor deposition , and sputtering .
- **vapor plating**
    - Deposition of a metal or compound on a heated surface by reduction or decomposition of a volatile compound at a temperature below the melting points of the deposit and the base material. The reduction is usually accomplished by a gaseous reducing agent such as hydrogen. The decomposition process may involve thermal dissociation or reaction with the base material. See also vacuum deposition .
- **V-bend die**
    - A die commonly used in press-brake forming, usually machined with a triangular cross-sectional opening to provide two edges as fulcrums for accomplishing three-point bending.
- **vent**
    - A small opening in a foundry mold for the escape of gases.
- **vermicular graphite iron**
    - Same as compacted graphite iron .
- **vibratory finishing**
    - A process for deburring and surface finishing in which the product and an abrasive mixture are placed in a container and vibrated.
- **Vickers hardness number (HV)**

  - A number related to the applied load and the surface area of the permanent impression made by a square-based pyramidal diamond indenter having included face angles of 136°, computed from:

$$\mathrm{HV} = 2P\sin\frac{\alpha/2}{d^2} = \frac{1.8544P}{d^2}$$

  - where *P* is applied load (kgf), ***d*** is mean diagonal of the impression (mm), and α is the face angle of the indenter (136°).
- **Vickers hardness test**
  - A microindentation hardness test employing a 136° diamond pyramid indenter (Vickers) and variable loads, enabling the use of one hardness scale for all ranges of hardness--from very soft lead to tungsten carbide. Also known as diamond pyramid hardness test. See also microindentation and microindentation hardness number .
- **virgin metal**
  - Same as primary metal .
- **void**
  - (1) A shrinkage cavity produced in castings or weldments during solidification. (2) A term generally applied to paints to describe holidays, holes, and skips in a film.
- **V process**
  - A molding (casting) process in which the sand is held in place in the mold by vacuum. The mold halves are covered with a thin sheet of plastic to retain the vacuum.
- **W**
- **walking-beam furnace**
  - A continuous-type heat treating or sintering furnace consisting of two sets of rails, one stationary and the other movable, that lift and advance parts inside the hearth. With this system, the moving rails lift the work from the stationary rails, move it forward, and then lower it back onto the stationary rails. The moving rails then return to the starting position and repeat the process to advance the parts again.
- **Wallner lines**
  - A distinct pattern of intersecting sets of parallel lines, sometimes producing a set of V-shaped lines, sometimes observed when viewing brittle fracture surfaces at high magnification in an electron microscope. Wallner lines are attributed to interaction between a shock wave and a brittle crack front propagating at high velocity. Sometimes Wallner lines are misinterpreted as fatigue striations.
- **warm working**
  - Deformation of metals at elevated temperatures below the recrystallization temperature. The flow stress and rate of strain hardening are reduced with increasing temperature; therefore, lower forces are required than in cold working. See also cold working and hot working .
- **warpage**
  - (1) Deformation other than contraction that develops in a casting between solidification and room temperature. (2) The distortion that occurs during annealing, stress relieving, and high-temperature service.
- **wash**
  - (1) A coating applied to the face of a mold prior to casting. (2) An imperfection at a cast surface similar to a cut (3) .
- **wash metal**
  - Molten metal used to wash out a furnace, ladle, or other container.
- **waterjet/abrasive waterjet machining**
  - A hydrodynamic machining process that uses a high-velocity stream of water as a cutting tool. This process is limited to the cutting of nonmetallic materials when the jet stream consists solely of water. However, when fine abrasive particles are injected into the water stream, the process can be used to cut harder and denser materials. Abrasive waterjet machining has expanded the range of fluid jet machining to include the cutting of metals, glass, ceramics, and composite materials.
- **water quenching**
  - A quench in which water is the quenching medium. The major disadvantage of water quenching is its poor efficiency at the beginning or hot stage of the quenching process. See also quenching .

- **waviness**
  - A wavelike variation from a perfect surface, generally much larger and wider than the roughness caused by tool or grinding marks.
- **wax pattern**
  - A precise duplicate, allowing for shrinkage, of the casting and required gates, usually formed by pouring or injecting molten wax into a die or mold. See also investment casting .
- **wear**
  - Damage to a solid surface, generally involving progressive loss of material, due to a relative motion between that surface and a contacting surface or substance. Compare with surface damage .
- **wear debris**
  - Particles that become detached in a wear process.
- **wear pad**
  - In forming, an expendable pad of rubber or rubberlike material of nominal thickness that is placed against the diaphragm to lessen the wear on it. See also diaphragm (2) .
- **weathering**
  - Exposure of materials to the outdoor environment.
- **weathering steels**
  - Copper-bearing high-strength low-alloy steels that exhibit high resistance to atmospheric corrosion in the unpainted condition.
- **weave bead**
  - A type of weld bead made with transverse oscillation.
- **web**
  - (1) A relatively flat, thin portion of a forging that effects an interconnection between ribs and bosses; a panel or wall that is generally parallel to the forging plane. See also rib . (2) For twist drills and reamers, the central portion of the tool body that joins the lands. (3) A plate or thin portion between stiffening ribs or flanges, as in an I-beam, H-beam, or other similar section.
- **weight percent**
  - Percentage composition by weight. Contrast with atomic percent .
- **weld**
  - A localized coalescence of metals or nonmetals produced either by heating the materials to suitable temperatures, with or without the application of pressure, or by the application of pressure alone with or without the use of filler metal.
- **weldability**
  - The capacity of a material to be welded under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service.
- **weld bead**
  - A deposit of filler metal from a single welding pass.
- **weld crack**
  - A crack in weld metal.
- **weld decay**
  - Intergranular corrosion, usually of stainless steels or certain nickel-base alloys, that occurs as the result of sensitization in the heat-affected zone during the welding operation. See also sensitization .
- **welding**
  - (1) Joining two or more pieces of material by applying heat or pressure, or both, with or without filler material, to produce a localized union through fusion or recrystallization across the interface. The thickness of the filler material is much greater than the capillary dimensions encountered in brazing. (2) May also be extended to include brazing and soldering. (3) In tribology, adhesion between solid surfaces in direct contact at any temperature.
- **welding current**
  - The current in the welding circuit during the making of a weld.
- **welding cycle**
  - The complete series of events involved in the making of a weld.
- **welding electrode**
  - See electrode (welding) .
- **welding ground**
  - Same as work lead .

- **welding leads**
  - The electrical cables that serve as either work lead or electrode lead of an arc welding circuit.
- **welding machine**
  - Equipment used to perform the welding operation. For example, spot welding machine, arc welding machine, seam welding machine, etc.
- **welding rod**
  - A form of filler metal used for welding or brazing that does not conduct the electrical current, and which may be either fed into the weld pool or preplaced in the joint.
- **welding sequence**
  - The order in which the various component parts of a weldment or structure are welded.
- **welding stress**
  - Residual stress caused by localized heating and cooling during welding.
- **welding tip**
  - A welding torch tip designed for welding.
- **welding torch (arc)**
  - A device used in the gas tungsten and plasma arc welding processes to control the position of the electrode, to transfer current to the arc, and to direct the flow of shielding and plasma gas. See also gas tungsten arc welding and plasma arc welding .
- **welding torch (oxyfuel gas)**
  - A device used in oxyfuel gas welding, torch brazing, and torch soldering for directing the heating flame produced by the controlled combustion of fuel gases. See also oxyfuel gas welding .
- **welding wire**
  - A form of welding filler metal, normally packaged as coils or spools, that may or may not conduct electrical current depending on the welding process with which it is used. See also electrode (welding) and welding rod .
- **weld interface**
  - The interface between weld metal and base metal in a fusion weld, between base metals in a solid-state weld without filler metal, or between filler metal and base metal in a solid-state weld with a filler metal and in a braze.
- **weld line**
  - See preferred term weld interface .
- **weldment**
  - An assembly whose component parts are joined by welding.
- **weld metal**
  - That portion of a weld that has been melted during welding.
- **weld nugget**
  - The weld metal in spot, seam or projection welding. See also nugget and resistance spot welding .
- **weld pass**
  - A single progression of a welding or surfacing operation along a joint, weld deposit, or substrate. The result of a pass is a weld bead, layer, or spray deposit.
- **weld pool**
  - The localized volume of molten metal in a weld prior to its solidification as weld metal.
- **weld puddle**
  - See preferred term weld pool .
- **weld reinforcement**
  - Weld metal in excess of the quantity required to fill a joint.
- **Wenstrom mill**
  - A rolling mill similar to a universal mill but where the edges and sides of a rolled section are acted on simultaneously.
- **wet blasting**
  - A process for cleaning or finishing by means of a slurry of abrasive in water directed at high velocity against the workpieces.
- **wetting**
  - (1) The spreading, and sometimes absorption, of a fluid on or into a surface. (2) A condition in which the interface tension between a liquid and a solid is such that the contact angle is 0° to 90°. (3) The phenomenon whereby a liquid filler metal or flux spreads and adheres in a thin continuous layer on a solid base metal.

- **wetting agent**
    - (1) A substance that reduces the surface tension of a liquid, thereby causing it to spread more readily on a solid surface. (2) A surface-active agent that produces wetting by decreasing the cohesion within the liquid.
- **whisker**
    - (1) A short single crystal fiber or filament used as a reinforcement in a matrix. Whisker diameters range from 1 to 25 μm, with aspect ratios (length to diameter ratio) generally between 50 and 150. (2) Metallic filamentary growths, often microscopic, sometimes formed during electrodeposition and sometimes spontaneously during storage or service, after finishing.
- **white-etching layer**
    - A surface layer in a steel that, as viewed in a section after etching, appears whiter than the base metal. The presence of the layer may be due to a number of causes, including plastic deformation induced by machining or surface rubbing, heating during a metallographic preparation stage to such an extent that the layer is austenitized and then hardened during cooling, and diffusion of extraneous elements into the surface.
- **whiteheart malleable**
    - See malleable iron .
- **white iron**
    - A cast iron that is essentially free of graphite, and most of the carbon content is present as separate grains of hard Fe_3C. White iron exhibits a white, crystalline fracture surface because fracture occurs along the iron carbide platelets.
- **white layer**
    - (1) Compound layer that forms in steels as a result of the nitriding process. (2) In tribology, a white-etching *layer*, typically associated with ferrous alloys, that is visible in metallographic cross sections of bearing surfaces. See also Beilby layer .
- **white metal**
    - (1) A general term covering a group of white-colored metals of relatively low melting points based on tin or lead. (2) A copper matte of about 77% Cu obtained from smelting of sulfide copper ores.
- **white rust**
    - Zinc oxide; the powder product of corrosion of zinc or zinc-coated surfaces.
- **Widmanstätten structure**
    - A structure characterized by a geometrical pattern resulting from the formation of a new phase along certain crystallographic planes of the parent solid solution. The orientation of the lattice in the new phase is related crystallographically to the orientation of the lattice in the parent phase. The structure was originally observed in meteorites, but is readily produced in many alloys, such as titanium, by appropriate heat treatment.
- **wildness**
    - A condition that exists when molten metal, during cooling, evolves so much gas that it becomes violently agitated, forcibly ejecting metal from the mold or other container.
- **winning**
    - Recovering a metal from an ore or chemical compound using any suitable hydrometallurgical, pyrometallurgical, or electrometallurgical method.
- **wiped coat**
    - A hot dipped galvanized coating from which virtually all free zinc is removed by wiping prior to solidification, leaving only a thin zinc-iron alloy layer.
- **wiped joint**
    - A joint made with solder having a wide melting range and with the heat supplied by the molten solder poured onto the joint. The solder is manipulated with a hand-held cloth or paddle so as to obtain the required size and contour.
- **wiper forming, wiping**
    - Method of curving sheet metal sections or tubing over a form block or die in which this form block is moved relative to a wiper block or slide block.
- **wiping effect**
    - Activation of a metal surface by mechanical rubbing or wiping to enhance the formation of conversion coatings, such as phosphate coatings.
- **wire**

    - (1) A thin, flexible, continuous length of metal, usually of circular cross section, and usually produced by drawing through a die. The size limits for round wire sections range from approximately 0.13 mm (0.005 in.) to 25 mm (1 in.). Larger rounds are commonly referred to as bars. See also flat wire . (2) A length of single metallic electrical conductor, it may be of solid, stranded or tinsel construction, and may be either bare or insulated.
- **wire bar**
    - A cast shape, particularly of tough pitch copper, that has a cross section approximately square with tapered ends, designed for hot rolling to rod for subsequent drawing into wire.
- **wire drawing**
    - Reducing the cross section of wire by pulling it through a die.
- **wire flame spraying**
    - A thermal spraying process variation in which the material to be sprayed is in wire or rod form. See also flame spraying .
- **wire rod**
    - Hot-rolled coiled stock that is to be cold drawn into wire.
- **wiring**
    - Formation of a curl along the edge of a shell, tube, or sheet and insertion of a rod or wire within the curl for stiffening the edge. See also curling .
- **woody structure**
    - A macrostructure, found particularly in wrought iron and in extruded rods of aluminum alloys, that shows elongated surfaces of separation when fractured.
- **work hardening**
    - Same as strain hardening .
- **working electrode**
    - The test or specimen electrode in an electrochemical cell.
- **work lead**
    - The electrical conductor connecting the source of arc welding current to the work. Also called work connection, welding ground, or ground lead.
- **worm**
    - An exudation (sweat) of molten metal forced through the top crust of solidifying metal by gas evolution. See also zinc worms .
- **wrap forming**
    - See stretch forming .
- **wrinkling**
    - A wavy condition obtained in deep drawing of sheet metal, in the area of the metal between the edge of the flange and the draw radius. Wrinkling may also occur in other forming operations when unbalanced compressive forces are set up.
- **wrought iron**
    - A commercial iron consisting of slag (iron silicate) fibers entrained in a ferrite matrix.
- **X**
- **x-ray**
    - A penetrating electromagnetic radiation, usually generated by accelerating electrons to high velocity and suddenly stopping them by collision with a solid body. Wavelengths of x-rays range from about 10^{-1} to 10^{-2} Å, the average wavelength used in research being about 1 Å. Also known as roentgen ray or x-radiation. See also electromagnetic radiation .
- **x-ray diffraction (XRD)**
    - An analytical technique in which measurements are made of the angles at which x-rays are preferentially scattered from a sample (as well as of the intensities scattered at various angles) in order to deduce information on the crystalline nature of the sample--its crystal structure, orientations, and so on.
- **x-ray fluorescence**
    - Emission by a substance of its characteristic x-ray line spectrum on exposure to x-rays.
- **x-ray map**
    - An intensity map (usually corresponding to an image) in which the intensity in any area is proportional to the concentration of a specific element in that area.
- **x-ray photoelectron spectroscopy (XPS)**

  - An analytical technique that measures the energy spectra of electrons emitted from the surface of a material when exposed to monochromatic x-rays.
- **x-ray spectrometry**
  - Measurement of wavelengths of x-rays by observing their diffraction by crystals of known lattice spacing.
- **x-ray spectrum**
  - The plot of the intensity or number of x-ray photons versus energy (or wavelength).
- **x-ray topography**
  - A technique that comprises topography and x-ray diffraction. The term topography refers to a detailed description and mapping of physical (surface) features in a region. In the context of the x-ray diffraction, topographic methods are used to survey the lattice structure and imperfections in crystalline materials.
- **Y**
- **Y-block**
  - A single keel block .
- **yellow brass**
  - A name sometimes used in reference to the 65Cu-35Zn type of brass.
- **yield**
  - (1) Evidence of plastic deformation in structural materials. Also known as plastic flow or creep. See also flow . (2) The ratio of the number of acceptable items produced in a production run to the total number that were attempted to be produced. (3) Comparison of casting weight to the total weight of metal poured into the mold.
- **yield point**
  - The first stress in a material, usually less than the maximum attainable stress, at which an increase in strain occurs without an increase in stress. Only certain materials--those that exhibit a localized, heterogeneous type of transition from elastic to plastic deformation--produce a yield point. If there is a decrease in stress after yielding, a distinction may be made between upper and lower yield points. The load at which a sudden drop in the flow curve occurs is called the upper yield point. The constant load shown on the flow curve is the lower yield point.
- **yield point elongation**
  - In materials that exhibit a yield point, the difference between the elongation at the completion and at the start of discontinuous yield.
- **yield strength**
  - The stress at which a material exhibits a specified deviation from proportionality of stress and strain. An offset of 0.2% is used for many materials, particularly metals. Compare with tensile strength .
- **yield stress**
  - The stress level of highly ductile materials at which large strains take place without further increase in stress.
- **Young's modulus**
  - A term used synonymously with modulus of elasticity. The ratio of tensile or compressive stresses to the resulting strain. See also modulus of elasticity .
- **Z**
- **zinc worms**
  - Surface imperfections, characteristic of high-zinc brass castings, that occur when zinc vapor condenses at the mold/metal interface, where it is oxidized and then becomes entrapped in the solidifying metals.
- **zincrometal**
  - A steel coil-coated product consisting of a mixed-oxide underlayer containing zinc particles and a zinc-rich organic (epoxy) topcoat. It is weldable, formable, paintable, and compatible with commonly used adhesives. Zincrometal is used to protect outer body door panels in automobiles from corrosion.
- **zone melting**
  - Highly localized melting, usually by induction heating, of a small volume of an otherwise solid metal piece, usually a metal rod. By moving the induction coil along the rod, the melted zone can be transferred from one end to the other. In a binary mixture where there is a large difference in composition on the liquidus and solidus lines, high purity can be attained by concentrating one of the constituents in the liquid as it moves along the rod.

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